



PIPELINE CELERITIES

by

John Hodgson

UNIVERSITY OF ALBERTA

1983 M. Eng.



THE UNIVERSITY OF ALBERTA

RELEASE FORM

NAME OF AUTHOR JOHN EDMUND HODGSON

TITLE OF THESIS PIPELINE CELERITIES

DEGREE FOR WHICH THESIS WAS PRESENTED MASTER OF ENGINEERING

YEAR THIS DEGREE GRANTED SPRING 1983

Permission is hereby granted to THE UNIVERSITY OF ALBERTA LIBRARY to reproduce single copies of this thesis and to lend or sell such copies for private, scholarly or scientific research purposes only.

The author reserves other publication rights, and neither the thesis nor extensive extracts from it may be printed or otherwise reproduced without the author's written permission.

(SIGNED) *John Hodgson*

PERMANENT ADDRESS:

21 Grandora Crescent

St. Albert, Alberta

T8N 0T8

DATED: April 15, 1983

STANLEY ASSOCIATES ENGINEERING
LIBRARY

E 5114

THE UNIVERSITY OF ALBERTA

PIPELINE CELERITIES

by

JOHN EDMUND HODGSON

A THESIS

SUBMITTED TO THE FACULTY OF GRADUATE STUDIES AND RESEARCH
IN PARTIAL FULFILMENT OF THE REQUIREMENTS FOR THE DEGREE
OF MASTER OF ENGINEERING

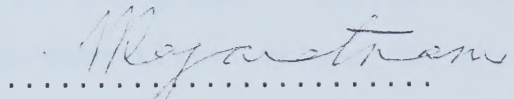
CIVIL ENGINEERING

EDMONTON, ALBERTA

SPRING 1983

THE UNIVERSITY OF ALBERTA
FACULTY OF GRADUATE STUDIES AND RESEARCH

The undersigned certify that they have read, and recommend to the Faculty of Graduate Studies and Research, for acceptance, a thesis entitled PIPELINE CELERITIES submitted by JOHN EDMUND HODGSON in partial fulfilment of the requirements for the degree of MASTER OF ENGINEERING.


.....
Supervisor


.....
Reader

Date: April 15, 1983



Digitized by the Internet Archive
in 2025 with funding from
University of Alberta Library

Abstract

This paper presents a detailed discussion of pipeline celerity. The relevant equations used in the calculation of pipeline celerities for homogeneous pipe, composite pipe and tunnels are discussed. The properties of water, other fluids and commonly used pipe wall materials are discussed. In addition, the effects of entrained air and soil confinement--factors largely ignored in the consideration of pipeline celerities--are discussed and means to estimate their impact on pipeline celerities are given. Tables are developed giving the most representative values for the celerities of all sizes and classes for each of several (eight) types of commercial pipe used in the conveyance of water. Celerity calculations were performed using a computer program which used the most probable material property values and pipe dimensions taken from the appropriate set of manufacturing standards.

Acknowledgements

The author would like to thank the many people who have helped in the review and preparation of this paper:

Dr. N. Rajaratnam from the University of Alberta--Advisor; Mr. A. W. Peterson from the University of Alberta--Reader; Dr. I. B. Joliffe from the University of Alberta--review and comments; Dr. C. P. Liou from Stoner Associates, Inc.--review and comments; Mr. D. G. Tyrrell from Du Pont Canada, Inc.--review and comments on polyethylene pipe; Mr. T. R. Roulston from Manville Canada, Inc.--provision of data and comments on transite, polyvinyl chloride and Permastran pipe; and, Ms. P. Larsen from Stanley Associates Engineering Ltd.--typing of tables.

In addition, the author would like to express his sincere gratitude to his employer (Stanley Associates Engineering Ltd.) and his family (Patti, Daniel and Megan) for their support of his academic activities over the past three years.

Chapter	Table of Contents	Page
1.	INTRODUCTION	1
2.	EQUATIONS, CONCEPTS AND MATERIAL PROPERTIES	4
2.1	GENERAL	4
2.2	CELERITY EQUATIONS	5
2.2.1	Thin Walled Elastic Pipelines	6
2.2.2	Thick Walled Elastic Pipelines	7
2.2.3	Circular Tunnels	9
2.2.4	Linings For Pipelines	10
2.2.5	Composite Pipe Sections	12
2.2.6	Air Entrainment Effects	15
2.3	MATERIAL PROPERTIES	18
2.3.1	Water	18
2.3.2	Other Fluids	20
2.3.3	Pipe Walls	21
2.3.4	Soils	22
2.3.5	Rock	25
3.	CELERITIES FOR HOMOGENEOUS PIPE	26
3.1	STEEL PIPE	26
3.2	DUCTILE IRON PIPE	28
3.3	COPPER TUBING	30
3.4	CAST IRON PIPE	32
3.5	ALUMINUM PIPE	34
3.6	ASBESTOS CEMENT (TRANSITE) PIPE	35
3.7	POLYVINYL CHLORIDE PIPE	38
3.8	POLYETHYLENE PIPE	42
4.	CELERITIES FOR OTHER CONDUITS	46

4.1 WOOD STAVE PIPE	46
4.2 CONCRETE PRESSURE PIPE	49
4.2.1 General	49
4.2.2 Descripton of Standards	50
4.2.3 Material Properties	52
4.2.4 Celerity Considerations	55
4.3 FIBERGLASS REINFORCED PVC PIPE	58
4.4 CIRCULAR TUNNELS	59
5. CONCLUSIONS	61
Bibliography	65

List of Tables

Table 2.1	Pipeline Constraint Factors for Thin and Thick Walled Pipes
Table 2.2	Cement Mortar Linings for Steel Pipe
Table 2.3	Cement Mortar Linings for Cast and Ductile Iron Pipes
Table 2.4	Celerities for Air/Water Mixtures
Table 2.5	Properties and Sonic Velocities of Water
Table 2.6	Properties of Some Common Fluids
Table 2.7	Typical Pipeline Material Properties
Table 2.8	Modulus of Elasticity for Selected Soils
Table 2.9	Modulus of Soil Reaction for Selected Bedding Materials
Table 2.10	Modulus of Soil Reaction for Various Bedding Types
Table 2.11	Modulus of Elasticity for Selected Rock Groups
Table 3.1	Celerities for Unlined Steel Pipe
Table 3.2	Celerities for Unlined Ductile Iron Pipe
Table 3.3	Celerities for Copper Tubing
Table 3.4	Celerities for Unlined Cast Iron Pipe
Table 3.5	Celerities for Aluminum Pipe
Table 3.6	Celerities for Asbestos Cement (Transite) Distribution Pipe
Table 3.7	Celerities for Asbestos Cement (Transite) Transmission Pipe
Table 3.8	Celerities for PVC Pipe (4 to 12 inches)
Table 3.9	Celerities for Polyethylene Pipe

Table 4.1	Elastic Modulus for Plank Decking by Species Group
Table 4.2	Celerities for Continuous Wood Stave Pipe
Table 4.3	Celerity Range for Continuous Wood Stave Pipe
Table 4.4	Celerities for Concrete Pressure Pipe
Table 4.5	Celerities for Permastran Pipe
Table 4.6	Typical Tunnel Celerities
Table 5.1	Summary of Celerity Equation Applications

List of Figures

Figure 1	Typical Pipe Installation
Figure 2	Concrete Pressure Pipe Force Balance

Note: Tables and Figures are located at end of paper (beginning at page 70).

Nomenclature

Symbols:

- a celerity or pressure wave velocity (fps)
- c pipeline constraint factor
- d inside diameter of pipe (inches)
- n torsion modulus (psi)
- p density of fluid (sl/ft³)
- t wall thickness of pipe (inches)
- u Poisson's ratio
- A cross-sectional area of pipe (ft²)
- E elastic (Young's) modulus (psi)
- H depth of burial (feet)
- K bulk modulus (psi)
- V volume (ft³)
- γ specific heat ratio

Subscripts:

- c concrete
- d design
- e equivalent or effective
- g gas
- l liner or liquid
- p pipe
- r rock (for elasticity) or rupture (for tensile strength)
- s soil

1. INTRODUCTION

The calculation of the celerity (the speed of propagation of a pressure impulse) for a complex pipeline cross-sectional configuration requires the combined knowledge of the waterhammer phenomenon and strength of materials analysis. For homogeneous pipes the formulations for pipeline celerity are relatively simple. However, in carrying out waterhammer investigations the determination of celerities can be repetitious and tedious; there are a large number of pipe material types, pressure classes and sizes that can be used in any given system.

To assist in the analysis of complex pipelines there are simplified procedures for calculating celerity presented in the literature. To relieve the tedium of pipeline celerity calculations for common pipes there are some charts and tables available in the literature (Parmakian, 1963; Johns-Manville Corporation, 1977). However, the more prominent references in waterhammer literature have not combined the pipeline celerity equations with the known properties of standard pipe materials, classes and sizes available in the marketplace today.

This paper outlines the various procedures for determining pipeline celerities and some of the factors which affect the behaviour of the celerity of a pipeline during transient conditions. Also presented is a summary of common pipeline material properties and a discussion of the factors which may be of significance in celerity

calculations. This is the result of a review of the technical literature, the technical and product specifications of the pipe manufacturers, the American Water Works Association (AWWA) standards, the American Society for Testing Materials (ASTM) specifications, and the Canadian Standards Association (CSA) specifications. As a result, tables of pipeline celerities are presented which will be invaluable to the design engineer when carrying out waterhammer analysis.

This paper is presented primarily to facilitate transient analysis in municipal systems where the fluid being conveyed is water. The analysis of pipe materials and standards reflects this in the discussion. Many of the pipe types discussed herein are also used in applications for the transmission of other fluids. In these cases the formulations still apply but the resulting pipeline celerities will vary from the values presented herein.

Due to the Government of Canada's metrification program pipes in Canada will soon all be specified in System International (SI) units. Most pipe manufacturers in Canada will be making soft conversions to metric dimensions in order to maintain consistency with other manufacturers in the United States and compatibility with existing pipe. English units are used throughout this paper as, at present, most standards, specifications and manufacturers literature also use these units.

The numerical values for pipeline celerities presented in the tables are given to the nearest five feet per second (fps). This is intended to reflect the precision (significant figures) to which these values have been calculated and not the accuracy to which these values are to be found in the field. The calculation precision is actually greater as all calculations were done either by a computer program or on a programmable calculator.

The celerities for several types of pipe are highly variable, depending on a number of factors which will be discussed in due course. In practice, the celerities will be more than sufficiently accurate for most transient analyses. Adjustments of up to 10% are often made (particularly for transients in pipe networks) to establish a representative system that can be analysed (with a reasonable cost) by the method of characteristics solution to the unsteady flow equations (Stoner Associates, 1981).

2. EQUATIONS, CONCEPTS AND MATERIAL PROPERTIES

2.1 GENERAL

In a completely rigid and incompressible medium a pressure impulse is transmitted from one point to another instantaneously. For an infinite compressible medium impulses are transmitted at finite wave celerities (or sonic velocities) which are dependent on the density and the elastic properties of the medium. The velocity of a waterhammer pressure wave in a completely rigid pipe filled with an elastic fluid is given by the same equation as that for the sonic velocity (a) in an infinite homogeneous elastic fluid.

$$a = \gamma \sqrt{\frac{K}{\rho}} \quad (2.1)$$

In equation 2.1 γ is the ratio of specific heats of the fluid, ρ is the density and K is the bulk modulus. In a liquid, the specific heat ratio can be ignored as it is nearly unity for an incompressible liquid (Pearsall, 1965). For water at 50 degrees Fahrenheit, the specific heat ratio has a value of 1.001.

The sonic velocity is the maximum pressure wave velocity (pipeline celerity) possible. Elastic pipelines that convey elastic fluids have celerities less than the

sonic velocity. The celerity of an elastic pipeline is a function of the fluid and pipe wall material properties, the pipe diameter and wall thickness, and the external pipeline constraint conditions. There are several presentations in the literature which address the derivation of pipeline celerities for simple and complex cross-sectional configurations (Halliwell, 1963; Parmakian, 1963; Wylie and Streeter, 1978). These will form the basis of much of the subsequent discussion in Section 2.2.

2.2 CELERITY EQUATIONS

A positive pressure impulse on a compressible fluid inside an elastic pipeline is accommodated by the compression of the fluid, the lengthening of the pipeline, and an increase in the diameter of the pipe due to the stretching of the pipe walls. Consideration of these concepts results in the general pipeline celerity equation (figure 1):

$$a = \frac{\sqrt{K/p}}{\sqrt{1 + \frac{dKc}{tE}}} \quad (2.2)$$

where E is the elastic modulus, d the inside diameter and t the wall thickness of the pipeline. The value of the

pipeline constraint factor (c) accounts for the various physical factors which are representative of the constraint of the pipeline.

2.2.1 Thin Walled Elastic Pipelines

For the case where the ratio of the pipeline's inside diameter to its wall thickness (d/t) is large, any circumferential and longitudinal stresses in the pipe wall encompassing a fluid element are evenly distributed. Solution of the continuity and momentum equations for several constraint conditions with this thin walled assumption results in simple relationships for their respective pipeline constraint factors (Halliwell, 1963):

Case a - pipeline anchored at upstream end only:

$$c = 5/4 - u \quad (2.3)$$

Case b - pipeline anchored against longitudinal motion:

$$c = 1 - u^2 \quad (2.4)$$

Case c - pipeline with expansion joints:

$$c = 1 \quad (2.5)$$

where u is Poisson's ratio.

There are discrepancies in the equations given in the literature for these constraint factors. The three prominent derivations of these are by Halliwell (1963), Parmakian (1963), and Wylie and Streeter (1978). Wylie and Streeter differ from the above equations for Case a; all agree on Case b; and Parmakian differs for Case c. Wylie and Streeter's derivation for Case a differs because it omitted the longitudinal strain of the pipeline (they derived $c = 1-u/2$). Parmakian's derivation for Case c differs because, with expansion joints, he neglected to observe that the overall length change for a pipeline would be zero (coincidentally, he also had $c = 1-u/2$).

2.2.2 Thick Walled Elastic Pipelines

For pipes in which the walls are thick relative to the diameter (i.e. d/t is small) the stresses in the pipe walls are not uniformly distributed. The effect of considering this in the derivation of the pipeline constraint factors is to reduce the pipeline celerity further from the values calculated using the thin walled formulations. The evaluation of these pipeline constraint factors has been presented in detail by Halliwell (1963). The thick walled formulations of the constraint factors for the same three types of pipeline constraint discussed previously for thin walled pipes are as follows:

Case a - pipeline anchored at upstream end only:

$$c = \frac{2t}{d} (1 + u) + \frac{d}{d + t} \left(\frac{5}{4} - u\right) \quad (2.6)$$

Case b - pipeline anchored against longitudinal motion:

$$c = \frac{2t}{d} (1 + u) + \frac{d}{d + t} (1 - u^2) \quad (2.7)$$

Case c - pipeline with expansion joints:

$$c = \frac{2t}{d} (1 + u) + \frac{d}{d + t} \quad (2.8)$$

It can be seen from these that, as d/t approaches infinity, the c values approach the values for the thin walled approximations.

Wylie and Streeter (1978) indicated that the thick walled equations should be used when d/t is less than 25. They also indicated that, for the thick walled cases, the effects of the type of constraint are not significant. Assuming a value of 0.3 for u , the variation between the thin walled and thick walled values for the constraint factors decrease as d/t increases (Table 2.1). When $d/t = 40$ the variation in c is less than 5%--a more reasonable point for differentiating between the use of the two

formulations. This is a reasonable concept but it does not address the relative effects of the pipeline stiffness and the fluid compressibility. It will later be shown that the use of the thick walled equations is of more importance for the more elastic pipes.

With respect to the type of pipeline constraint, it was found that the constraint factor varies in the order of 6% to 10% for d/t ranging from 5 to infinity (Table 2.1). This is in contradiction with Wylie and Streeter's statement--within the range of d/t expected for commercial pipe significant variation in the values of the pipeline constraint still exists.

2.2.3 Circular Tunnels

The celerity equation for unlined circular tunnels can most easily be determined by taking a special case of the thick walled pipe constraint formulation (Watters, 1979). For any of the pipeline constraint factor formulations, the limit of $d*c/t$ as t approaches infinity is $2(1 + u)$. As a result, the celerity in unlined circular tunnels is given by:

$$a = \frac{\sqrt{K/p}}{\sqrt{1 + \frac{2K(1+u)}{E_r}}} \quad (2.9)$$

where the subscript r denotes the tunnel material. Note that the tunnel diameter has no effect on the celerity of unlined tunnels.

For tunnels that are lined with concrete and steel Halliwell (1963) presents equations which will account for the effects of the linings. The effect of the tunnel liner (which is usually stiffer than the material through which the tunnel is driven) is to increase the celerity. For the case of tunnels having a single liner, the increase in celerity that this causes can be included in the calculation by using equation 2.2 and the constraint factor:

$$c = \frac{2Et}{\frac{E_r d}{1+u} + 2Et} \quad (2.10)$$

In this equation the writer has inserted $(1+u)$ in the denominator--a term which was not included in Halliwell's work. This was included to allow the equation to converge to equation 2.9 for the case when t approaches zero. Halliwell (1963) also presents equations for more complex tunnel lining configurations.

2.2.4 Linings For Pipelines

Steel, cast iron and ductile iron pipelines are often lined to prevent internal corrosion. The effect of the pipe lining is to increase the celerity. This effect, or the overall effect of any pipe made of two or more materials,

can be accounted for by converting the individual thicknesses to a common thickness based on the modulus of elasticity. For a lined pipe:

$$t_e = t_p + \frac{t_l E_l}{E_p} \quad (2.11)$$

where the subscripts p, l, and e denote the pipe, the lining and the equivalent pipe wall, respectively.

Halliwell (1963) suggests that the equivalent wall thickness be based on the material in contact with the fluid. This is appropriate since the internal diameter is the value used in the pipeline celerity equation. However, since liners are usually more elastic than the pipe wall material, it is suggested that the equivalent thickness be based on the pipe material. This allows for a better indication as to the effects of the lining (versus unlined pipe) and the validity of the thin walled assumption.

There are many materials used to coat and wrap pipe to provide both internal and external corrosion protection. The materials covered by AWWA standards include taped coatings, coal-tar epoxy, fusion-bonded epoxy, and cement mortar lining. Cement mortar lining is one of the more commonly used lining materials for pipelines. Of the common lining materials it will have the greatest tendency to increase pipeline celerity due to its relatively high elastic modulus and the greater thickness to which it is

applied. Cement mortar lining is covered in AWWA standards C205 for steel pipe and C104 for cast iron and ductile iron pipe. Tables 2.2 and 2.3 present the thicknesses and tolerances of linings required for these pipe.

Examination of the tables indicate that the effects of cement mortar lining are greatest on the stronger, thinner walled materials (i.e. steel is affected more than ductile iron, which is affected more than cast iron). Also, the effects of cement mortar lining are greater on larger diameter pipes due to the increased associated lining thickness required in the standards. For the iron pipes the celerity increases that result from lining effects are less than 2% and can be ignored. However, for steel pipe 12 inches in diameter or greater, lining effects should be included in celerity calculations when the pipe is lined with cement mortar.

2.2.5 Composite Pipe Sections

There are several types of pipe in use today that make use of more than one material in their construction. This allows the manufacturer to take advantage of the best properties of each material to produce a pipe with good performance characteristics and reasonable cost. Pipes of this type that have been commonly manufactured include wood stave pipe, reinforced and prestressed concrete cylinder (or noncylinder) pipe, fiberglass reinforced polyvinyl chloride pipe, and fiberglass pipe.

There are three methods that can be used for the determination of celerity in this type of pipe:

1. converting the pipe material thickness to an equivalent homogeneous pipe.
2. developing a pressure-strain curve for the pipe, and
3. making field measurements of celerity.

In converting a heterogeneous pipe into an equivalent homogeneous pipe one transforms the materials to the equivalent thickness of the material with the highest modulus of elasticity:

$$A_e = \frac{A_1 E_1}{E_1} + \dots + \frac{A_i E_i}{E_1} \quad (2.12)$$

where A denotes the circumferential area of the various materials per foot of width. For wood stave and concrete pipes one transforms the materials to the equivalent steel pipe. In doing so, one must be careful to consider which components actually carry the load (Watters, 1979). For concrete pressure pipe the exterior concrete coating is for corrosion protection only and should be ignored. As wood staves are not circumferentially secured there is reason to exclude these from the calculations as well. On the other hand, prestressing the steel may result in compression in the concrete or wood at normal operating pressures--this would be sufficient reason to include these materials in the celerity calculations.

Composite pipe sections could well have different celerity values for downsurge (low pressure) and upsurge (high pressure) waves. It is likely that the pipe would propagate downsurge waves faster than upsurge waves as there would be more material resisting the shrinkage in diameter (i.e. compressive stresses) than the expansion (i.e. tensile stresses).

The development of a pressure-strain curve is a more rigorous analysis which makes use of a different form of the denominator in equation 2.2 (Wylie and Streeter, 1978):

$$a = \frac{\sqrt{K/p}}{\sqrt{1 + \frac{K \Delta A}{A \Delta P}}} \quad (2.13)$$

where P denotes the pipeline's internal pressure.

This type of analysis was carried out for concrete pressure pipe by Kennison (1956). The simplified homogeneous pipe transformation approach discussed in the previous paragraphs assumed that the composite effect of the pipe wall materials would be linearly elastic throughout the full range of pressure variation. For reinforced concrete cylinder pipe this is not true. Kennison indicated that up to the pressure producing incipient cracking in the concrete the slope of the pressure-strain curve is essentially that of the composite concrete/steel pipe wall. Above the cracking pressure, the slope of the pressure-strain curve

flattens until it is parallel with that of the steel pipe wall only. From the pressure-strain curve the celerity can be determined using equation 2.13. This procedure can be similarly applied to other composite pipe sections as well.

Field measurements of the pipeline celerity of composite pipe have been made for concrete pressure pipe (Kennison, 1956) and for fiberglass reinforced polyvinyl chloride pipe (Watters et al, 1976). This type of testing is of great value in the assessment of the procedures for calculating pipeline celerities. However, field measurement is too costly and lacks the expedience to be of any practical value to the design engineer.

2.2.6 Air Entrainment Effects

Entrained air has the potential to dramatically lower the celerity in a pipeline. For this reduction to occur there must be free air in the fluid in the form of bubbles distributed throughout. Air can enter a pipeline by several means:

1. air can be entrapped during pipeline filling at local high points,
2. air can be drawn in at the point where water enters the pipeline (e.g. at the pump suction bell or the entrance to a gravity pipeline),
3. air can be released from solution when there is a pressure reduction or a temperature increase, and
4. air can enter through air inlet valves or vacuum

breakers along the pipeline when negative pressures occur.

The proper design and operation of a piping system will eliminate free air in the system from the first three sources during normal operations. However, during a transient which generates low or negative pressures air can be entrained in the fluid by the latter two means.

The celerity equation (2.2) can be modified to determine the pressure wave velocity in the gas/liquid mixture. The effective bulk modulus of the mixture is given by:

$$K_e = \frac{K_l}{1 + \frac{V_g}{V} \left[\frac{K_l}{K_g} - 1 \right]} \quad (2.14)$$

where the subscripts e, g and l denote the effective, gas and liquid values respectively. Similarly, the effective density of the mixture is:

$$\rho_e = \rho_g \frac{V_g}{V} + \rho_l \frac{V_l}{V} \quad (2.15)$$

If the pipe wall is stiff relative to water the effects of the pipe can conservatively be ignored since the addition of air makes the mixture more elastic. The celerity equation (2.2) simply becomes:

$$a = \sqrt{\frac{K_e}{Pe}} \quad (2.16)$$

If there is air present in the fluid and the pressures are high, the effects of the pipe wall become more important. Wylie and Streeter (1978) present a more complex equation to consider pipeline celerity under these conditions.

These equations are difficult to apply because the volume of free gas is difficult to estimate and is a function of pressure. Examination of the equations with some typical values gives an indication as to the significance of air entrainment in the reduction of pipeline celerities. At a temperature of 45 degrees Fahrenheit and at atmospheric pressure water can accommodate 12 and 19 parts per million (by weight) of oxygen and nitrogen respectively (Sawyer and McCarty, 1967). If these came out of solution from saturated water during the low pressure period of a transient, the gas would occupy a volume of about 2 1/2 % of the total at atmospheric pressure. Table 2.4 gives an indication of how rapidly the celerity is reduced when only a small amount of air is present or comes out of solution.

It must be re-emphasized that there must be a mechanism for air to become entrained in the fluid before it can have this dramatic effect on pipeline celerity (i.e. negative pressures during the course of a transient). In transient analysis the effects of an air inlet valve or the column separation boundary condition would be the more appropriate

means for simulation and would allow the omission of the celerity change from the analysis. Wylie and Streeter (1978) indicate that the omission of the lower pipeline celerity is appropriate when column separation occurs at well defined locations. They also indicated that it is conservative when the locations are not well defined.

2.3 MATERIAL PROPERTIES

2.3.1 Water

Of the parameters involved in the determination of pipeline celerity the properties of the fluid being conveyed are of predominant importance. The fluid properties which affect pipeline celerity are density and bulk modulus. The general celerity equation (2.2) shows the significance of these. For relatively stiff pipeline materials, the denominator tends to unity, establishing the sonic velocity equation (2.1) as the upper limit for celerity. For pipelines of standard materials conveying water, the celerity will not exceed this value.

The physical properties of water vary with temperature and, as a result, the celerity (or sonic velocity) does not remain constant (Table 2.5). The range of sonic velocities for water from its freezing point to its boiling temperature is about 8%--the minimum celerity is 4616 fps at 32 degrees Fahrenheit and the maximum is 4993 fps at 120 degrees.

Water temperatures can vary considerably depending on the type of system, the time of year and the geographical location of the works being assessed. Canadian drinking water standards indicate that acceptable water temperatures for water supply are below 59 degrees Fahrenheit--the water quality objective for temperature is also 59 degrees (Health and Welfare Canada, 1979). In the determination of pipeline celerities that follows, a temperature of 45 degrees Fahrenheit is used for defining the properties of water (density = 1.940 slug/ft³; bulk modulus = 300,000 psi; sonic velocity = 4719 fps). This temperature is the probable ambient temperature in most Canadian municipal systems. The variation of sonic velocity over a reasonable range of temperatures (say, 32 to 60 degrees) is less than 2 1/2 %. In most cases celerity adjustment as a result of a variation in water temperature is not necessary. For a relatively stiff pipe material whose properties are not affected by temperature, temperature effects related to changes in the properties of the water can be approximately accounted for by factoring the celerity by the sonic velocity ratios given in Table 2.5.

Pearsall (1965) reports on the results of others who have made measurements of the acoustic velocity in distilled water. For the range of temperature we are concerned with here (about 32 to 68 degrees Fahrenheit) the acoustic velocity increases by only 1.5% as the ambient absolute fluid pressure increases from atmospheric (14.7 psi) to

2000 psi. Ambient water pressure is not a factor in pipeline celerity calculations.

2.3.2 Other Fluids

Although it is not the intention of this paper to discuss pipeline celerities in the context of fluids other than water, some representative properties of other fluids are presented in Table 2.6. These fluids have sonic velocities that vary considerably from that for water. The effect of the pipeline material on most fluids is to lessen the deviation of the pipeline celerity with respect to that for water (Table 2.6). However, the magnitude of these deviations make it evident that the celerities presented herein for pipelines conveying water are not to be considered as applicable to the same pipelines conveying other fluids. For each type of fluid to be conveyed there would be a number of factors that would have to be considered before making precise estimates of pipeline celerity (e.g. the variation of fluid properties with temperature and pressure; and the ambient system temperature and pressure).

2.3.3 Pipe Walls

For a homogeneous isotropic material, the following equations relate the various elastic properties of the substance (Yarwood and Castle, 1968):

$$\text{Elastic Modulus} \quad E = \frac{9nK}{3K + n} \quad (2.17)$$

$$\text{Poisson's Ratio} \quad u = \frac{E}{2n} - 1 \quad (2.18)$$

$$\text{Bulk Modulus} \quad K = \frac{E}{3(1 - 2u)} \quad (2.19)$$

$$\text{Torsion Modulus} \quad n = \frac{E}{2(1 + u)} \quad (2.20)$$

In determining pipeline celerities we are interested in the elastic (Young's) modulus and Poisson's ratio only. Table 2.7 gives representative values of these for a number of common pipe wall materials. For tunnels, the elastic properties of rock are sometimes expressed as the torsion modulus (modulus of rigidity). Values for the elasticity of rock are presented in Section 2.3.5.

For pipe strength considerations we also need to know the minimum yield stress or the ultimate strength of a ductile or a brittle pipe wall material, respectively. For a given pipe wall material there are sometimes several grades of alloys available with varying strength characteristics. Considerations relevant to this aspect of waterhammer analysis will not be discussed further in this

paper. The manufacturers' literature should be examined carefully for a given application so the appropriate strength characteristics are used in any assessment.

2.3.4 Soils

The backfill around a pipe has the tendency to increase the velocity of an upsurge (high pressure wave). This is caused by the confining effect that the backfill has on the pipe. The soil generates additional resistance to the expansion of the pipe as an upsurge is being transmitted. The soil, however, would have no influence on the speed of a downsurge (low pressure wave) as the pipe contraction would pull its walls away from the soil. It is quite conceivable, then, that a buried, highly elastic pipe could have two distinct celerities--a higher value related to the upsurge and a lower value related to the downsurge.

The effect of soil confinement is more pronounced in the more elastic pipe (i.e. polyethylene and polyvinyl chloride) where the ratio of the soil elasticity to the pipe wall material elasticity is the largest. Watters et al (1976) made laboratory measurements of the celerity of buried and unburied polyvinyl chloride (PVC) pipe. From these they found that burial increased the pipeline celerity for upsurges by about 7%. They did not measure the celerity of downsurges so the effects burial on downsurges were not shown. It is reasonable to expect the effects of confinement to be even more profound on polyethylene pipe.

As the cement-type and metal pipes have elastic moduli an order of magnitude larger than those for the plastic pipes it is understandable that the effect of burial on the celerity of the stiffer pipes is negligible.

In this paper the effects of soil confinement on celerity will be quantified by the use of the lined tunnel equations (equations 2.2 and 2.10) with a Poisson's ratio of 0.0 for the soil. This would be a reasonable approach where there was a large depth of burial for the pipe (i.e. a large value of H/d). It is not the intention of this work to investigate how celerity varies with H/d --although it will be shown later that the celerities measured by Watters et al can be calculated using the lined tunnel equation with reasonable values for the soil properties (even though his tests were on shallow buried pipe). In this paper it is assumed that this is an appropriate procedure.

The modulus of elasticity for soils is of interest to engineers in the determination of the settlement of buildings and of the deflection and stresses in buried pipe. Considerable work has been carried out in the area of foundation analysis. The modulus of elasticity (E_s) can be determined by plotting stress-strain curves for unconfined or triaxial compression tests or from plate load tests (Bowles, 1968). For granular soils E_s has been found to be sensitive to the depth (increasing with greater depth) due to lateral confinement. E_s for these cohesionless soils has been found to be independent of the soil moisture content.

For cohesive soils the opposite is true. E_s for these is independent of depth but is highly dependent on the soil moisture content.

Typical values of E_s for foundation soils are presented in Table 2.8. It is believed that these values are inappropriate for use in assessing the effects of soil confinement on pipes. This is because the foundation problem can be generalized as a compressive stress imposed on the surface of a semi-infinite solid whereas the buried pipe problem is that of radial compressive stresses just below the surface of a semi-infinite solid.

Investigations of the deflection and the stresses in buried pipe provide more useful information for soil properties as they relate to pipeline celerities. In this type of study the soil's elasticity is termed the modulus of reaction (E').

For years researchers have been trying to evaluate E' (Kennedy, 1976). Typically, the load on and the deflection of a buried pipe is measured and E' is backcalculated from a deflection formula using an assumed value for the bedding angle of the soil. Other procedures have been developed to allow the calculation of E' without the bedding angle assumption.

Tables 2.9 and 2.10 show suggested values for E' to be used in deflection calculations for buried pipe. As well, Table 2.10 shows the values of E' determined by Kennedy from field tests. These values of E' range from 50 psi to 3000

psi--being highest for well compacted, granular soils. They are much less than the range of values for E_s suggested for foundation soils.

2.3.5 Rock

Knowledge of the elastic properties of rock is required in order to determine the celerities for tunnels. The range of values for the modulus of elasticity of selected rock groups is shown in Table 2.11.

3. CELERITIES FOR HOMOGENEOUS PIPE

In this section values for the celerities of a number of commercially available homogeneous pipe are presented. The celerities are presented in a tabular fashion. They have been computed based on the thick walled equations for the appropriate constraint type and typical material property values. The significance of using the thick walled equations, the variation in material properties and the effects of burial on the computed celerities are discussed to determine the degree of confidence one should have in the values presented. Also, if these pipe are sometimes supplied with a lining material, the effects of this on the pipeline celerity are discussed. Generally, the tabulated values will be considered sufficiently accurate if the possible deviations are within plus or minus 3%.

In addition, field measurements that have been made by others of celerities in commercial pipe have been reported. Where possible it has been attempted to justify the observed values by use of reasonable values of material properties and constraint conditions.

3.1 STEEL PIPE

Steel pipe has been used for conveying water in the United States since 1852. The characteristics of significance which favour the use of steel as a pipe wall material are its strength and its ductility. Steel pipe

usually finds application when the flow and pressure are great and when there are difficult natural or artificial obstacles in the path of the pipeline (AWWA, 1964). In early applications steel pipe was riveted but nowadays almost all connections using steel pipe are welded, threaded or flanged. The specifications for the manufacture of steel pipe are covered in AWWA Standard C200.

There are several grades of steel that are used in the manufacture of steel pipe. For steel the modulus of elasticity varies between 28,000,000 psi and 31,000,000 psi depending on the grade of material (Miner and Seastone, 1955; Pearsall, 1965). The value most commonly used for the elastic modulus of steel pipe is 30,000,000 psi (AWWA, 1964). All sources indicate that Poisson's ratio for steel is 0.30.

Celerities for common sizes of unlined steel pipe are presented in Table 3.1. These have been computed using the thick walled equation for the Case b constraint. Use of the thin walled equation would result in an increase in the computed celerities of 0.4% to 0.8%, depending on the pipe diameter and the pipe wall thickness. Therefore, the thin walled approximation would normally be satisfactory for computing the celerity of steel pipe. The confining effects of burial produced no significant increase in the computed celerities; therefore, these effects can be ignored for steel pipe.

Variation throughout the range of possible values for the elastic modulus resulted in computed celerities that had a deviation of, at most, 2.4% from the values presented in Table 3.1. As a result, the celerities that are presented in Table 3.1 can be considered as accurate.

The effects of a cement mortar lining on the pipeline celerities of steel pipe has been addressed in Section 2.2.4. For steel pipe 12 inches in diameter or larger the effects of cement mortar lining should be included in celerity calculations. A celerity increase of over 3.0% was computed due to the lining of a 48 inch diameter steel pipe.

3.2 DUCTILE IRON PIPE

Ductile iron pipe usage has increased in recent years; the pipe has replaced cast iron pipe in most applications (ASCE, 1975). Advantages of ductile iron are its high strength, excellent impact resistance and, like cast iron, better corrosion characteristics than steel. Ductile iron is also easier to machine than cast iron.

The first standard for the manufacture of ductile iron pipe was adopted in 1965. The specifications for the manufacture of ductile iron pipe are covered in AWWA standards C150 and C151. Ductile iron pipe is usually centrifugally cast. Like steel it is designed as a flexible conduit. Pipe lengths are usually joined with integral bell and spigot joints. The pipe is often cement mortar lined

and encased in polyethylene jackets to improve its hydraulic characteristics and to provide better corrosion protection.

Ductile iron used in the manufacture of pipe contains about 3.5% carbon. This carbon is in the form of spheroids or nodules. This allows the material to have high strength and ductility characteristics more like steel than cast iron. All sources indicated a value of 24,000,000 psi for the modulus of elasticity (AWWA C150; Watters, 1979; Johns-Manville, 1977). Poisson's ratio has been presented as 0.28 (Watters, 1979) and 0.29 (Johns-Manville, 1977).

Celerities for common sizes and classes of ductile iron pipe are presented in Table 3.2. These have been computed using the thick walled equation for the Case c constraint. Use of the thin walled equation results in an increase in the computed celerities of 0.4% to 1.0%, depending on the pipe diameter and the pipe wall thickness. Therefore, the thin walled approximation would normally be satisfactory for computing the celerity of ductile iron pipe. The confining effects of burial produced no significant increase in the computed celerities; therefore, these effects can be ignored for ductile iron pipe.

The variation of the elastic modulus by 1,000,000 psi would result in computed celerities that would, at most, be 1.1% different from the celerities presented in Table 3.2. The effects of using the different values for Poisson's ratio had a negligible effect on the computed celerities. As a result, the celerity values presented in Table 3.2 can

be considered as accurate.

The effects of cement mortar lining on the celerity of ductile iron pipe has been addressed in Section 2.2.4. For ductile iron pipe the maximum increase in celerity due to lining is less than 1.6%--the effects of lining can be ignored.

3.3 COPPER TUBING

Copper tubing has been utilized for a variety of applications since 1924 (American Brass Company). This pipe is used extensively for plumbing and heating applications. The standards for the manufacture of copper tubing are covered in ASTM Specification B88.

Copper tubing is supplied in either hard or soft temper. Soft temper copper allows the coiling of smaller diameter pipe for ease of handling but, it also reduces the design bursting pressure of the pipe. Hard temper copper tubing comes only in straight lengths. Pipe lengths and fittings for copper pipe are joined by soldered connections.

There are two wall thickness types for copper tubing commonly used in pressure pipe applications (American Brass Company; Crane Municipal Waterworks Catalogue). Type K is heavy wall tube and is generally recommended for gas, steam, hot water, underground services, industrial piping or wherever there are relatively severe installation and service conditions. Type L is medium wall tube and is

recommended for general plumbing work under less severe conditions such as interior applications for water, heating, gas, steam, and oil lines.

There are a variety of copper alloys which are used in the manufacture of copper tubing. The most common is Phosphorized Copper-103. This alloy has a composition of 99.95% copper and 0.04% phosphorous. The modulus of elasticity for this material is 17,000,000 psi (Miner and Seastone, 1955). Pearsall (1965) reported a range of 15,600,000 psi to 19,000,000 psi for the elastic modulus of copper. Poisson's ratio for copper is 0.34 (Yarwood and Castle, 1968).

Celerities for common sizes of copper tubing are presented in Table 3.3. These have been computed using the thick walled equation for the Case a constraint. Use of the thin walled equation results in an increase in the computed celerities of 0.9% to 1.3%, depending on the pipe diameter and the pipe wall thickness. Therefore, the thin walled approximation would normally be satisfactory for computing the celerity of copper tubing. The confining effects of burial produced no significant increase in the computed celerities; therefore, these effects can be ignored for copper tubing.

Variations in material properties would not likely result in dramatically different celerity values. Computations of celerity using the range of values for the modulus of elasticity resulted in a maximum deviation of

1.8% from the values presented in Table 3.3. As a result, the celerities presented in Table 3.3 can be considered as accurate.

3.4 CAST IRON PIPE

Cast iron pipe was widely used in the past due to its high strength characteristics. Today, ductile iron pipe has largely replaced cast iron pipe in manufacture and use (ASCE, 1975).

The first American standard for the manufacture of cast iron pipe was adopted in 1902. Presently, the specifications for the manufacture of cast iron pipe is covered in AWWA standards C101, C106, and C108. Pipe lengths are usually joined by integral bell and spigot joints. Cast iron pipe is either centrifugally cast or pit-cast. The centrifugally cast pipe is made by rotating the molten metal in a mold. Cast iron pipe may be dipped in or coated with coal tar enamel or lined with cement mortar to increase the pipe's corrosion resistance and to improve its hydraulic characteristics.

Grey cast iron used in the manufacture of pipe contains about 3.5% carbon. This carbon is in the form of graphite flakes making the material more brittle than most other metals used in the manufacture of pipe. The modulus of elasticity for grey cast iron has a range of 11,600,000 psi to 18,600,000 psi (Pearsall, 1965; Yarwood and Castle,

1968). A value of 15,000,000 psi is usually used in design (AWWA C101). Poisson's ratio has been given values ranging from 0.23 to 0.31 (Yarwood and Castle, 1968). Pearsall (1965) indicates a value of 0.25 and Johns-Manville (1977) indicate a value of 0.29. An average value of 0.27 is used in this paper.

Celerities for common sizes and classes of cast iron pipe are presented in Table 3.4. These have been computed using the thick walled equation for the Case c constraint. Use of the thin walled equation results in an increase in the computed celerities of 0.8% to 1.6%, depending on the pipe diameter and the pipe wall thickness. Therefore, the thin walled approximation would normally be satisfactory for computing the celerity of cast iron pipe. The confining effects of burial produced no significant increase in the computed celerities; therefore, these effects can be ignored for cast iron pipe.

The variation of the elastic modulus would result in computed celerities that would, at most, be 5.5% different from the celerities presented in Table 3.4. The effects of using different values for Poisson's ratio had a negligible effect on the computed celerities. As a result, the celerity values presented in Table 3.4 can be considered as accurate if the modulus of elasticity has a value close to 15,000,000 psi.

The effects of cement mortar lining on the pipeline celerities of cast iron pipe has been discussed in Section

2.2.4. For cast iron pipe the maximum increase in the computed celerity due to lining is about 1.5%--the effects of lining can be ignored.

3.5 ALUMINUM PIPE

Aluminum pipe is frequently used for handling fluids due to its light weight, its high strength to weight ratio, its non-sparking nature, its non-toxicity, and its corrosion resistance. As a result of these favourable characteristics aluminum pipe is found used for irrigation or other movable pipe applications, in the handling of explosive materials, in explosive or inflammable environments, and in the handling of food products.

The manufacture of aluminum pipe is governed by ASTM specifications B241 and B483. There are a variety of aluminum alloys which are used in the manufacture of aluminum pipe. The most common aluminum alloys are type 1S (99.5% aluminum) and type 65ST (a high strength alloy). For aluminum, the modulus of elasticity has a range of 9,900,000 psi to 10,700,000 psi (Miner and Seastone, 1955). A value of 10,200,000 psi represents a typical value for the grades most often used in the manufacture of aluminum pipe. Poisson's ratio has a range of 0.33 to 0.35 (Watters, 1979; Yarwood and Castle, 1968).

Celerities for common sizes and schedules of aluminum pipe are presented in Table 3.5. These have been computed

using the thick walled equation for the Case c constraint. Use of the thin walled equation results in an increase in the computed celerities of 1.0% to 2.3%, depending on the pipe diameter and pipe wall thickness. Therefore, the thin walled approximation would normally be satisfactory for computing the celerity of aluminum pipe. The confining effects of burial produced no significant increase in the computed celerities; therefore, these effects can be ignored for aluminum pipe.

The variation of the elastic modulus would result in computed celerities that would, at most, be 1.4% different from the celerities presented in Table 3.5. The effects of using different values for Poisson's ratio had negligible effect on the computed celerities. As a result, the celerity values presented in Table 3.5 can be considered as accurate.

3.6 ASBESTOS CEMENT (TRANSITE) PIPE

Asbestos cement pipe was introduced to North America in 1931 after several years of satisfactory usage in other countries, particularly Italy. The use of asbestos cement pipe increased until, in recent years, it was one of the more popular pipe materials in use for water distribution piping and the transmission of water and other fluids. This pipe material (also called transite) consists of a matrix of asbestos fibres bonded by portland cement. It is resistant

to tuberculation, encrustation, soil corrosion and electrolysis. A special slip-type sleeve joint is used to join lengths of pipe.

There are four AWWA standards which govern the design of two types of transite pipe. AWWA standards C400 and C401 are concerned with distribution piping from 4 to 16 inches in diameter. This range of pipe sizes was chosen due to the potential waterhammer effects of rapidly closing fire hydrants in water distribution systems. It was philosophized that the damage potential for these surges are significant yet the analysis of transient conditions and the implementation of surge protection equipment are both uneconomical and impracticable for pipe in this size range. To allow for this, transite distribution pipe has a factor of safety of at least 4.0 applied to its design internal pressure (pipe class).

The second type of transite pipe is covered by AWWA standards C402 and C403. These address the design of transmission pipe from 18 to 42 inches in diameter. For large transmission lines the general application of a large factor of safety would significantly increase the cost of the pipe. Relatively, it becomes more economical to analyse transient conditions and utilize surge protection equipment on large transmission lines. As a result, transite transmission pipe has a smaller factor of safety (2.0) applied. In using this type of pipe consideration must be given to transient conditions to ensure that the design

internal pressures are not exceeded.

The most commonly used value for the modulus of elasticity of transite is 3,400,000 psi (Kessler, 1939; Parmakian, 1963; Pearsall, 1965; Wylie and Streeter, 1978; Watters, 1979). Johns-Manville indicates a value of 3,000,000 psi. Test results presented by Kessler on asbestos cement pipe indicated a range of values from 3,110,000 psi to 3,475,000 psi. This paper uses the more commonly accepted value of 3,400,000 psi.

The most commonly used value for the Poisson's ratio of transite is 0.30 (Parmakian, 1963; Watters, 1979). Johns-Manville indicates a value of 0.20. This paper uses Johns-Manville's value of 0.20.

Celerities for common sizes and classes of transite pipe are presented in Tables 3.6 and 3.7. These have been computed using the thick walled equation for the Case c constraint. Use of the thin walled equation results in an increase in the computed celerity of 2.0% to 4.4%, depending on the pipe diameter and the pipe wall thickness. Therefore, the thin walled approximation is inadequate for computing the celerity of transite pipe (particularly for the larger diameter, thicker walled pipe). The confining effects of burial produced no significant increase in the computed celerities; therefore, these effects can be ignored for transite pipe.

Variations in the values of the material properties would not likely result in dramatically different celerity

values. Computations of celerity using the range of values for the modulus of elasticity resulted in a maximum deviation of about 4.3% from the values presented in Tables 3.6 and 3.7. Using the range of values for Poisson's ratio resulted in a maximum deviation of about 0.5%--the computed celerities are relatively insensitive to Poisson's ratio. As a result, the celerities in Tables 3.6 and 3.7 can be considered as accurate if the modulus of elasticity has a value close to 3,400,000 psi.

Field measurements of the celerity of 14 inch Class 150 transite pipe have been carried out by Kessler (1939). He found celerities ranging from 3210 fps to 3450 fps. The median value of 3335 fps compares well with that presented in Table 3.6.

3.7 POLYVINYL CHLORIDE PIPE

Polyvinyl Chloride (PVC) pipe was developed in Europe in the late 1930's (Scepter Manufacturing Company, 1973; Uni-Bell, 1982). It was introduced in the United States shortly after World War II and in Canada in 1951. Since its introduction, the market for PVC has steadily expanded as the suitability of its unique combination of characteristics has become more appreciated. PVC is a non-toxic material that has good hydraulic characteristics and is resistant to bacterial growth, corrosion and electrolytic action. Its light weight allows for easy installation of the pipe. It

has been used for small water supply systems, sewage forcemains and as municipal water distribution piping. PVC pipe can be joined in a number of manners (e.g. solvent welding, fusion welding, threaded or flanged connections). For distribution piping, integral bell and spigot joints are most commonly used.

There are two sets of standards for the manufacture of PVC pipe--those of the American Water Works Association and those of the Canadian Standards Association. Pipe made to AWWA Standard C900 is commonly referred to as 'class' pipe. This standard has dimensions for steel and cast iron outside diameter pipe. Diameter to thickness ratios are given for three pressure classes--100, 150 and 200.

Pipe made to CSA specifications is commonly referred to as 'series' pipe. The dimensions and design requirements are given in CSA Standard B137.3. Diameter to thickness ratios are given for four pressure series--100, 125, 160 and 200. Ratios are also given for two pipe schedule numbers--40 and 80. All outside diameters of CSA specified pipe are equivalent to steel pipe.

Plastic materials generally are classified in two basic groups--thermoplastics and thermosetting resins. The thermoplastics can be reformed repeatedly by application of heat. On the other hand, once a thermoset has been cured, its shape is fixed and it cannot be changed for reuse. PVC is a thermoplastic material with a higher tensile strength and modulus of elasticity than most other plastics. The

material itself is a hard brittle material at room temperature (Koleske and Wartman, 1969). However, with the addition of plasticizers PVC can possess a broad spectrum of physical properties. Of the several types of PVC material used in the manufacture of PVC pipe, the most commonly used is PVC 1120.

In addition to parameters related to the chemical nature of a particular PVC compound, the modulus of elasticity is dependent on the temperature and the strain rate. Nass (1977) indicated that, below room temperature, the tensile modulus for PVC is only moderately temperature dependent. The effects of the strain rate, based on elastic modulus determination tests, were more significant; unfortunately, the results of Nass's work are not easily related to pipeline celerity considerations.

Johns-Manville has indicated that the tensile modulus of elasticity for PVC 1120 has a range of values from 400,000 psi to 500,000 psi. The AWWA and CSA standards indicate a value of 400,000 psi. Scepter Manufacturing Company (1973) and Cabot Piping Systems (1966) indicate a value of 415,000 psi. Hucks (1981) found the modulus of elasticity to be 472,000 psi. Watters et al (1976) carried out tests on PVC pipe and obtained a value of 435,000 psi. From celerity measurements they backcalculated E and believed it to have a value closer to 450,000 psi. Ten values for the modulus of elasticity were found; these had a median value of about 425,000 psi. This is the value used

in this paper.

Poisson's ratio is seldom quoted for elastomers but is usually assumed to be between 0.40 and 0.50 (Harper, 1975). Values of 0.34, 0.38, 0.42 and 0.46 have been indicated by Scepter Pipe (1973), Uni-Bell (1982), Hucks (1981), and Johns-Manville (1977), respectively. An average value of 0.40 is used in this paper.

Celerities for common sizes and classes and series of PVC pipe are presented in Table 3.8. These have been computed using the thick walled equation for the Case c constraint. Use of the thin walled equation results in an increase in the computed celerities of 2.4% to 7.6%, depending on the pipe diameter and the pipe wall thickness. Therefore, the thin walled approximation is inadequate for computing the celerity of PVC pipe.

Variation of the values for Poisson's ratio had a negligible effect on the computed celerities. The variation of the elastic modulus would result in computed celerities that would differ by as much as 7.6% from the celerities presented in Table 3.8. As a result, the celerity values presented in Table 3.8 can be considered as accurate only if the modulus of elasticity has a value close to 425,000 psi. The tables do agree with Watters et al (1976) for the pipe that they tested. They found that 6 inch diameter Class 100 unburied PVC pipe had a measured celerity of 1120 fps; Table 3.8, with a value of 1125 fps, compares well.

The effects of burial are of significance for PVC pipe. An increase in the high pressure wave celerity can be expected in buried PVC pipe. An estimate of the celerities for buried PVC pipe is also presented in Table 3.8. Watters et al had measured a celerity of 1200 fps for the buried 6 inch diameter Class 100 PVC pipe. Again, with a value of 1210 fps, Table 3.8 is in close agreement.

3.8 POLYETHYLENE PIPE

Polyethylene (PE) pipe has been commercially available in North America since 1947 (Spzak and Rice, 1975). Early PE pipe was made from a 'low-density' polyethylene. This material was characterized by a randomly branched molecular structure. During the mid 1950's a type of polyethylene with a higher density was developed in Germany. This material had a linear and more compact molecular structure and higher strength and stiffness characteristics.

In the late 1950's a third type of PE appeared, having a 'controlled' or 'orderly' molecular structure. This is the preferred material for the manufacture of PE pipe in North America as the density (and, hence, the strength and stiffness characteristics) can be controlled. The density of polyethylene ranges from about 0.935 g/cc to 0.945 g/cc; materials with density less than 0.940 g/cc are designated type P23 or 'medium density' and those above are designated types P33 and P34 or 'high density'. In Canada, a further

designation--type P35--has still higher density, strength and stiffness characteristics than what are acknowledged in American standards.

Like PVC, polyethylene has excellent hydraulic characteristics and is resistant to bacterial growth, corrosion and electrolytic action. It, too, is light in weight, a factor which facilitates handling and installation. Polyethylene pipe has found popularity in such uses as water intakes, submarine crossings, sewage forcemains and other types of supply lines. The pipe has not been commonly used in water distribution systems due to difficulty in making service connections. However, for transmission lines pipe lengths are easily and soundly joined by butt fusion welding and transitions to other materials accommodated with flanged connections.

In Canada, polyethylene pipe is manufactured subject to CSA specifications B137.0 and B137.1. The pipe has several thickness classes (or series) which indicate the working pressure (psi) at 73 degrees Fahrenheit. Working pressures for polyethylene pipe range from 45 psi to 160 psi. Pipe from 3/4 inch to 48 inches in diameter is manufactured according to these standards. AWWA Standard C901 addresses only the manufacture of smaller (i.e. up to 3 inches) diameter pipe.

Polyethylene is a visco-elastic thermoplastic material. The modulus of elasticity is highly dependent on the temperature and duration of stress application (as a result,

the elastic modulus for a given set of conditions is called the apparent elastic modulus). For example, DuPont of Canada indicates that, at 39 degrees Fahrenheit, the apparent elastic modulus is about 225,000 psi for a load duration of about 2 seconds and decreases to about 155,000 psi for a load duration of 1 minute. Also, for a load duration of 1 minute, the apparent elastic modulus decreases to a value of about 85,000 psi at a temperature of 95 degrees (pers comm: Dave Tyrrell, DuPont of Canada). Other references indicate short duration elasticity values ranging from 100,000 psi to 150,000 psi (AWWA C901; Johns-Manville; DuPont, 1972; Cabot, 1966). Spzak and Rice (1975) indicated, based on shock loading tests, that the modulus of elasticity for type P35 polyethylene is about 155,000 psi (presumably, at 73 degrees--but, considering Tyrrell's comments, we will assume that this value is also appropriate for 45 degrees). This is the value used in this paper.

The apparent modulus of elasticity for polyethylene is also dependent on the stress level. This is not as significant a factor as the temperature and load duration effects. The values presented above are reasonable for high pipe wall stresses.

Values of 0.40 and 0.45 for Poisson's ratio have been presented by Johns-Manville (1977) and DuPont of Canada (1972), respectively. As DuPont are the major manufacturer and researcher of polyethylene pipe their value is accepted.

Celerities for common sizes and series of polyethylene pipe are presented in Table 3.9. These have been computed using the thick walled equation for the Case b constraint. Use of the thin walled equation results in an increase in the computed celerities of 4.0% to 17.0%, depending on the pipe diameter and the pipe wall thickness. Therefore, the thin walled approximation is inadequate for computing the celerity of polyethylene pipe.

The effects of using different values for Poisson's ratio had a negligible effect on the computed celerities. The variation of the elastic modulus would result in computed celerities that would be as much as 23% different from the celerities presented in Table 3.9. As a result, the celerity values presented in Table 3.9 can be considered as accurate for unburied pipe if the modulus of elasticity has a value close to 155,000 psi.

The effects of burial are of significance for polyethylene pipe. An estimate of the high pressure wave celerities of buried polyethylene pipe is also presented in Table 3.9. The celerity increase as the result of burial is in the range of 5% to 9%. Burial is a factor that is of great importance in determining the celerity of polyethylene pipe. To the writer's knowledge, there have been no field celerity measurements on buried polyethylene pipe.

4. CELERITIES FOR OTHER CONDUITS

4.1 WOOD STAVE PIPE

The utilization of wood as a piping material dates back to the Ancient Egyptians who used it for water service (Morrison, 1959). Bored logs were generally the means used to construct wooden pipelines in early history. This type of pipe was used extensively in seventeenth century England and, later, along the Atlantic Seaboard and in the Pacific Northwest of the United States. Wirewound wood stave pipe and continuous stave pipe gave the product the range in both size and service pressure to make it popular for water supply and hydroelectric projects during the late 19th and early 20th centuries. Its corrosion and abrasion resistance also made the pipe popular for conveying sewage or mine tailings.

Wirewound wood stave pipe is a factory built pipe which is manufactured in sizes up to twenty-four inches in diameter. Continuous stave pipe is prefabricated and then assembled on site. Larger diameter (2 feet to 20 feet) pipes are made this way from staves held together by steel bands instead of wire. Working pressures of 70 psi to 175 psi (depending on diameter) have been considered practical for the large diameter installations.

Continuous stave pipe were generally made from 'clear' or 'select' grade Douglas Fir. This material is native to

the coastal area of British Columbia and is noted for its high strength, length, straight grain, durability, water resistance and workability. As other woods have also been used in the manufacture of stave pipe the classification and the elastic modulus for each of several species groups are listed in Table 4.1. It should be noted that the 'clear' designation is no longer used in lumber grading. The modulus of elasticity for wood varies from 1,020,000 psi to 1,930,000 psi depending on the species of wood, the service conditions and the age of the installation.

The celerity of a wood stave pipe depends primarily on the steel bands and, to some extent, on the wood staves. A formulation for celerity presented by Rich (1963) uses an equivalent pipe wall thickness equation which assumes that the wood staves resist circumferential expansion. As continuous stave pipe is made of many staves which are connected along the longitudinal seams by a tongue and groove joint, it is not possible for the wood to accommodate tensile stress during an upsurge. However, as the wood is prestressed by the steel bands it would, to some extent, assist in the transmission of an upsurge. The wood staves would contribute to the transmission of a downsurge.

Parmakian (1963) considered that the transformation of all of the wood to the equivalent steel thickness would be the upper bound for calculating the celerity of wood stave pipes. He indicated that a lower limit for the celerity in wood stave pipes can be given by assuming no prestressing of

the wood exists and that the steel bands only transmit the pressure waves. A further reduction might be possible if one considers the longitudinal deflection of the staves themselves (however, as the maximum band spacing for continuous stave pipe is ten inches, this is unlikely). As a reasonable approximation of the effects of the wood staves Parmakian suggested that an equivalent steel pipe be used in determining celerity with one-sixtieth of the stave thickness added to the equivalent thickness of the steel bands. This is equivalent to assuming a value of 500,000 psi for the elastic modulus of the wood staves--about 1/3 of the probable value.

Celerities for continuous wood stave pipe at maximum band spacing (i.e. low pressure pipe) have been calculated by all three methods (Table 4.2). At the maximum band spacing these pipe have allowable working pressures of 13 psi to 33 psi (sewerage pipe). With the paucity of steel the effect of the wood is significant and the differences among the three methods of celerity calculation are most apparent. The use of Parmakian's method resulted in values that lie between the two extremes. The extreme values differ from the values determined by Parmakian by amounts ranging from 27% to 52%. In view of the variability of the elastic modulus for wood and its potential deterioration with age the method proposed by Parmakian appears to be the most reasonable approximation for the celerity of wood stave pipe. However, the deviations illustrated by the upper and

lower limits are so great that the accuracy of Parmakian's values for a given low pressure installation would not be great unless one knew the wood type and its condition.

The celerity in wood stave pipe is strongly dependent on the amount of steel wrapping the pipe (Table 4.3). Using the method of Parmakian for calculating celerity it was found that, for a given pipe diameter, the celerity increased by 50% to 60% over the range of working pressure. Therefore, for a given pipe it is imperative that one knows the band size and spacing in order to properly determine the pipeline celerity. With the greater amount of steel used in the high pressure wood stave pipe, the effects of the wood are reduced, and celerity calculation becomes more accurate--the largest deviation of Parmakian's method from the upper or lower limit celerity values for pipe with the maximum amount of steel is 16%.

4.2 CONCRETE PRESSURE PIPE

4.2.1 General

Concrete pressure pipe has been in use in North America since before 1940 (AWWA, 1979). This type of composite pipe makes use of the high tensile strength of steel and the compressive strength of concrete. In addition, the inherent corrosion inhibiting properties of concrete and cement mortar, and the relatively time-independent hydraulic

smoothness of cement mortar lining make the pipe useful for many applications.

Concrete pressure pipe can be manufactured with or without a thin steel sheet membrane (the membrane is sometimes deleted in low pressure pipe). For pipe with higher service pressures the steel membrane is used in conjunction with reinforcing rods or tensioned pre-stressing wires to provide sufficient steel to resist tensile stresses. Concrete pressure pipe is usually joined by push-on type, rubber gasketed bell and spigot joints that are fabricated onto one end of each pipe length.

There are presently four AWWA standards governing the design and manufacture of concrete pressure pipe. These will be discussed in the subsequent section prior to a discussion of the properties of concrete and the computation of the celerity of concrete pressure pipe.

4.2.2 Description of Standards

Reinforced Concrete Cylinder Pipe (C300)

This type of pipe was first manufactured in 1919. Reinforced concrete cylinder pipe was the most common type of concrete pressure pipe in use in the United States prior to the introduction of C301 pipe in the early 1940's (AWWA, 1979). This pipe has steel joint rings attached to the cylinder. This is placed inside one or more reinforcing cages between inside and outside forms. The concrete is

placed by vertical casting and is cured by the use of steam or water. Pipe of this type is manufactured with a range of size of 24 inches to 144 inches and with service pressures of up to 250 psi.

Prestressed Concrete Cylinder Pipe (C301)

Prestressed concrete cylinder pipe has been manufactured in the United States since 1942 (AWWA, 1979). There are two types of prestressed concrete cylinder pipe:

1. pipe with a steel cylinder lined with a concrete core, and
2. pipe with a steel cylinder embedded in a concrete core.

This pipe is manufactured by first attaching the joint assembly to the cylinder. The liner is either centrifugally spun into (lined) or vertically cast into (embedded) the cylinder. After curing, the assembly is helically wrapped with high strength steel wire stressed (to 75% of the minimum tensile strength--wrapping stress is 150,000 psi to 200,000 psi) to produce a predetermined amount of residual compression in the concrete core. The core assembly is covered with a cement slurry and then coated with cement mortar prior to final curing. Pipe of this type is available in diameters from 16 inches to 60 inches for the lined cylinder pipe and 24 inches to 144 inches for the embedded cylinder pipe. C301 pipe has been designed for operating pressures in excess of 400 psi.

Reinforced Concrete Noncylinder Pipe (C302)

This pipe does not have a watertight membrane (i.e. steel cylinder). As a result, reinforced concrete noncylinder pipe has limited application--it is used for operating pressures of 55 psi or less. This pipe is manufactured by the fabrication of one or more reinforcing cages with steel joint rings (if used). Concrete is placed either by vertical casting between two forms or by centrifugal casting within a single outside form. Pipe of this type is available in diameters from 12 inches to 144 inches.

Pretensioned Concrete Cylinder Pipe (C303)

The manufacture of pretensioned concrete cylinder pipe commences with the centrifugal lining of the steel cylinder/joint ring assembly with cement mortar. After curing, the core assembly is wrapped with hot-rolled steel bar at a moderate (8,000 psi to 10,000 psi) tension. This is covered with a cement slurry and then coated with cement mortar. Pipe of this type is available in diameters from 10 inches to 42 inches. Pipe with design pressures as high as 400 psi has been manufactured.

4.2.3 Material Properties

In order to determine the celerity of concrete pressure pipe one must know the properties and behaviour of steel and concrete. The elastic properties of steel are linear (i.e.

they obey Hooke's Law) throughout the range of pressures that the pipe is designed for. The elastic modulus for steel has been given earlier as 30,000,000 psi. The concrete, however, has properties which must be considered in more detail if an analysis more comprehensive than the equivalent pipe method is to be used for the determination of pipeline celerity. Properties of interest are the compressive strength, the tensile strength, the elastic modulus and Poisson's ratio.

The compressive strength of concrete (f'_c) is based on compression tests of concrete cylinders that are 28 days in age and have been cured at room temperature. There are many factors affecting the compressive strength of concrete. The strength increases with age, is ultimately higher if cured at a lower temperature, and varies with mix proportions, aggregate characteristics, type of cement and air content (Freedman, 1974). For concrete pressure pipe f'_c is usually 4500 psi.

The tensile strength of concrete is relatively low--about 10% to 15% of the compressive strength (Ferguson, 1979). The tensile strength is more difficult to measure and depends somewhat on the way in which it is measured. The modulus of rupture is a commonly measured tensile strength characteristic. This is somewhat larger than the real tensile strength. The modulus of rupture for concrete (f_r) can be estimated from the relation (Ferguson, 1979):

$$f_r = 7.5 \sqrt{f'_c} \quad (4.1)$$

For the design of reinforced concrete noncylinder pipe the design tensile strength (f_d) equation is (AWWA C302):

$$f_d = 4.5 \sqrt{f'_c} \quad (4.2)$$

The modulus of elasticity for concrete (E_c) is given by the equation:

$$E_c = 57,000 \sqrt{f'_c} \quad (4.3)$$

As the strength of concrete increases with time so does the modulus of elasticity. Kennison (1956) indicated that concrete (most likely with $f'_c = 4500$ psi) would have elastic modulus values of 3,750,000 psi, 5,000,000 psi and 6,000,000 psi at the ages of 1 year, 10 years and 100 years, respectively.

Poisson's ratio values for concrete are also variable. Values range from 0.11 to 0.27 with a most representative value of 0.20 at normal working stresses (Freedman, 1974). With an increase in strength, the value of Poisson's ratio for concrete decreases slightly. On the other hand, dynamic determinations of Poisson's ratio are higher than the

corresponding static values. Freedman indicates that the dynamic value of u is 0.03 higher for saturated normal weight concrete.

4.2.4 Celerity Considerations

From the writer's review of the literature Kennison (1956) is the only one to have investigated the more comprehensive method for the determination of the celerity of concrete pressure pipe. Although this calculation procedure is relatively simple, from the point of view of strength of materials analysis, its tediousness has led others (Wylie and Streeter, 1978; Watters, 1979) to propose only the equivalent pipe method. For general use in waterhammer analysis it is suggested that the more detailed calculations are not warranted for computing the celerity of concrete pressure pipe. However, this more complex type of analysis is invaluable in providing an understanding of how the pipe behaves during transient conditions. This type of analysis could also be applied to other composite pipe such as wood stave pipe.

Kennison's work does not describe the comprehensive calculation procedure in any detail. He presents the results of his work (shown here in Table 4.4) and describes the factors which are of importance in the calculations.

For any of the types of concrete pressure pipe one must establish a system of equations to describe the conditions of the various layers of concrete and steel (figure 2). The

first equation is for the force balance where the sum of the forces on all of the layers of material is equal to the internal pipe pressure times the wetted internal pipe diameter (with liner cracking this would likely be the inside diameter of the steel cylinder). To complete the equations one can develop a set of compatibility equations to describe the relative changes in the strains of the pipe components as the pressure increases. This consideration is important in order to determine how the load is shared between the steel and the concrete. As well, when the tensile stress in the concrete exceeds the modulus of rupture, the concrete must be deleted from the force and compatibility equations.

For a cross section with n layers of material we have n equations with the n stresses as unknowns (for embedded cylinder pipe n may be as high as 5). These equations can be easily solved by iteration. One starts the calculations with the internal pressure equal to zero and imposing any initial prestress conditions on the reinforcing. As the calculations are done for each subsequent pressure increase the celerity can be determined by computing dA/dP and using equation 2.13. Kennison proposed that the secant modulus to the rated surge pressure (40% to 50% above the working pressure) be used to determine the pipeline celerity. Kennison's term of secant modulus for the pressure-strain curve simply implies that the previously described calculations are done at zero pressure and the surge

pressure only.

Kennison found that reinforced concrete cylinder pipe (C300) operates at pressures which create concrete tensile stresses greater than the modulus of rupture. As a result, the slope of the pressure-strain curve is essentially that of the steel. For non-cylinder pipe (C302) the concrete must bear most of the tensile stresses and the celerity is governed by the concrete. The conditions with prestressed (C301) and pretensioned (C303) pipe are more complicated and, up to the point of incipient cracking of the concrete, both materials are factors in the pressure-strain curve.

Field measurements of the celerity in concrete pressure pipe were presented by Kennison which confirmed the results of his analyses. It appears as if measured pipeline celerities compared most favourably with the maximum values presented in Table 4.4.

This type of analysis tends to support the notion that the low pressure wave celerity is higher than the high pressure wave celerity. For a downsurge the concrete will be in compression and all materials will contribute to the celerity. For pressures of sufficient magnitude the concrete does not carry any tensile stress. For that matter, if a pipe is repeatedly subjected to high upsurge pressures, with time the concrete could crack until, eventually, only the steel will contribute to the high pressure wave celerity at any pressure. Whether this occurs or not in real life is only conjecture at this point. Of

the six projects for which Kennison reported celerity measurements, five supported the calculations which assumed that the concrete contributed to the celerity; only one test indicated that it did not.

4.3 FIBERGLASS REINFORCED PVC PIPE

Fiberglass reinforced PVC pipe was first introduced in North America in the 1970's. This pipe comprises a PVC core encased by a continuous roving fiberglass. The epoxy resin and fiberglass provide the strength to resist internal pressures while the PVC core provides the watertight conduit for conveying the fluid. This composite pipe has most of the advantageous properties of PVC and, due to the fiberglass, can withstand higher pressures with a lighter weight pipe. Pipe lengths are joined with integral bell and spigot joints.

The design and manufacture of fiberglass reinforced PVC pipe is governed by AWWA Standard C950. This standard was first issued in 1981. This type of pipe is primarily manufactured by Johns-Manville under the name of Permastran pipe. Permastran pipe is manufactured as Class 200 pipe--the class number reflects the rated working pressure of the pipe at 73 degrees Fahrenheit.

Celerity calculations for fiberglass reinforced PVC pipe would require the use of the thin walled equation applied to an equivalent pipe wall thickness. These

calculations would require knowledge of the fiberglass roving area and elasticity characteristics. Celerity values given by Johns-Manville (1977) for Class 200 Permastran pipe are presented in Table 4.5. Watters et al (1976) measured the celerity for a 6 inch diameter length of unburied Permastran pipe to be 1507 fps. Buried pipe had a measured celerity of 1555 fps (3.2% higher). The latter value is 1.3% less than the value presented by Johns-Manville. By inference, we can conclude that the values in the table are reasonable.

4.4 CIRCULAR TUNNELS

The celerity in a circular tunnel is strongly dependent on the material that the tunnel is bored through. The properties of the material are usually highly variable and difficult to predict. Bowles (1968) presented ranges for the properties of some selected rock groups (Table 2.11). Poisson's ratio for rock can vary between 0.1 and 0.4 but a typical value of 0.3 is assumed here. This is a necessary assumption in deriving the simplified equations for steel-lined tunnel celerities.

Celerities for lined and unlined tunnels of various diameters are presented in Table 4.6 to give an indication of the range for typical tunnel celerities. Equation 2.9 in Section 2.2.3 indicated that the celerity in unlined tunnels is independent of the tunnel diameter. For lined tunnels,

however, the tunnel diameter and lining thickness do have some effect on the celerity (equation 2.10 and Table 4.6).

5. CONCLUSIONS

1. The pipeline constraint equations for thin and thick walled pipes presented by Halliwell (1963) are correct. Wylie and Streeter's (1978) derivation for the Case a constraint is in error because they omitted the longitudinal strain of the pipeline. Parmakian's (1963) derivation for the Case c constraint is in error because he neglected to consider that the overall length change for the pipeline would be zero.
2. The effect of using the thick walled pipeline constraint equations versus the thin walled equations is to reduce the computed pipeline celerity. When d/t is greater than 40, the variation in the resulting c values is less than 5% (Table 2.1). However, one must also consider the K/E ratio. For water, it is reasonable to use the thin walled equations for commercially manufactured pipe of aluminum and those with stiffer pipe wall materials.
3. A significant (greater than 6%) difference between the computed pipeline constraints is possible regardless of the d/t ratio (Table 2.1). It is of importance to choose the proper pipeline constraint type.
4. The celerity for an unlined tunnel is independent of the conduit diameter. Equations 2.2 and 2.10 can be used to compute the celerity for a lined tunnel.
5. Lining a pipeline results in an increase in pipeline celerity. This effect can be considered using an equivalent wall thickness, based on the modulus of

elasticity, in the celerity calculation (equation 2.11). Cement mortar is the lining material that has the most significant effect on increasing pipeline celerity. For cast iron and ductile iron pipe the effects are negligible; increases of less than 2% were computed (Table 2.3). For steel pipe 12 inches in diameter and larger the effects are significant (Table 2.2).

6. The celerity of a composite pipe is most easily determined by transforming the materials to a single equivalent pipe wall thickness and using the thin walled equation. One must be careful to consider only the components which will actually carry the load. Induced compression in the concrete or wood of these type of pipe is sufficient reason to include these portions of the cross section in the calculations.
7. Composite pipe could well have different celerity values for low and high pressure waves. Low pressure waves would likely be faster as there is more material that could be considered to resist the pipe shrinkage (compressive stresses).
8. The presence of free air distributed throughout a fluid can dramatically reduce the pipeline celerity. The simplest formulation for this phenomenon conservatively assumes that the pipe wall is stiff relative to the liquid. For the celerity reduction to occur there must be a mechanism for the air to become entrained in the fluid.

9. The sonic velocity (equation 2.1) is the maximum pressure wave velocity (pipeline celerity) possible. For water, the maximum celerity is 4993 fps at 120 degrees Fahrenheit (Table 2.5).
10. Pipeline celerity is relatively unaffected by changes in the ambient temperature and pressure.
11. For a given pipe the pipeline celerity will vary significantly for fluids other than water.
12. The backfill around a highly elastic pipe has the tendency to increase the velocity of a high pressure wave. The effect of soil confinement is of significance for PVC and polyethylene pipe. The effects can be approximately considered by using the lined tunnel equation (2.10). As the pipe walls would tend to draw away from the soil, burial would likely have little effect on the low pressure wave celerity of a highly elastic pipe.
13. The modulus of reaction for a soil is more likely suitable for buried pipeline celerity calculations than the soil's modulus of elasticity.
14. Celerity calculations have been carried out for several pipe material types and configurations. The results are presented and discussed in sections 3 and 4 (see also tables 3.1 through 3.9 and 4.2 through 4.6). A summary of the results (Table 5.1) indicates that the thin walled equations are generally applicable for the stiffer pipe materials. More elastic pipe walls,

composite pipe, linings, tunnels, and burial of highly elastic pipe have effects on the pipeline celerity which are quantifiable through the use of ancillary calculations.

15. The method of Parmakian is a reasonable means to approximate the celerity of wood stave pipe. The condition and age of the wood and the steel band size and spacing must be known for an accurate estimate of the pipeline celerity.
16. Generally, the equivalent pipe method is a reasonable means to estimate the celerity of concrete pressure pipe.
17. The more comprehensive stress and strain analysis procedure can be applied to determine the celerity of a composite pipe and how it varies with pressure.

Bibliography

A. Literature

- ASCE, 1975. Pipeline design for water and wastewater. Committee on Pipeline Planning. Pipeline Division. American Society of Civil Engineers. New York, New York.
- AWWA, 1964. Steel pipe design and installation. AWWA Manual M11. Denver, Colorado.
- AWWA, 1979. Concrete pressure pipe. AWWA Manual M9. Denver, Colorado.
- Bowles, J. E., 1968. Foundation analysis and design. McGraw-Hill Book Company. New York, New York.
- Crane, 1969. Flow of fluids through valves, fittings, and pipe. Technical Paper No. 410-C. Chicago, Illinois.
- Ferguson, P. M., 1979. Reinforced concrete fundamentals. John Wiley. New York, New York.
- Freedman, S., 1974. Properties of materials for reinforced concrete. in: Handbook of Concrete Engineering, M. Fintel (editor). Van Nostrand. New York, New York.
- Glanvill, A. B., 1973. The plastics engineer's data book. Industrial Press. New York, New York.
- Halliwell, A. R., 1963. Velocity of a water-hammer wave in an elastic pipe. ASCE, Journal of the Hydraulics Division. Volume 89, Number 4.
- Harper, C. A. (editor), 1975. Handbook of plastics and elastomers. McGraw-Hill Book Company. New York, New York.
- Health and Welfare Canada, 1979. Guidelines for Canadian drinking water quality, 1978. Hull, Quebec.
- Hucks, R. T., 1981. Changes in strength of pressurized PVC pipe with time. AWWA Journal. July, 1981.
- Jeppson, R. W., G. H. Flammer and G. Z. Watters, 1972. Experimental study of water hammer in buried PVC and Permastran pipes. PRWG-113-1. Utah State University. Logan, Utah.

- Johns-Manville Corporation, 1977. Concepts of water-hammer and air entrapment in the filling and testing of pipelines. Recommendations resulting from a joint research effort of the Colorado State University and the Johns-Manville Corporation.
- Jones, R. M., 1975. Mechanics of composite materials. Scripta Book Company. Washington, D. C.
- Kennedy, H. Jr., 1976. The new ductile iron pipe standards. AWWA Journal. November, 1976.
- Kennison, H. F., 1956. Surge-wave velocity--concrete pressure pipe. Trans. ASME, 1956. 78, 1323.
- Kessler, L. H., 1939. Speed of water hammer wave in transite pipe. Trans. ASME, 1939. 61, 11.
- Koleske, J. V. and L. H. Wartman, 1969. Poly(vinyl chloride). Gordon Breach Science Publishers. New York, New York.
- LTIC, 1972. Timber design manual. Laminated Timber Institute of Canada. Ottawa, Ontario.
- Miner, D. F. and J. B. Seastone, 1955. Handbook of engineering materials. John Wiley. New York, New York.
- Morrison, L. F., 1959. Continuous stave wood pipe. Canadian Wood Pipe and Tanks Limited. Vancouver, British Columbia.
- Nass, L. I. (editor), 1977. Encyclopedia of PVC. 3 volumes. Marcel Dekker. New York, New York.
- Parmakian, J., 1963. Waterhammer analysis. Dover Publications. New York, New York.
- Pearsall, I. S., 1965. The velocity of waterhammer waves. Paper 2. Symposium on Surges in Pipelines. London, England.
- Rich, G. R., 1963. Hydraulic transients. Engineering Societies Monograph. Dover Publishers. New York, New York.
- Sawyer, C. N. and P. L. McCarty, 1967. Chemistry for sanitary engineers. McGraw-Hill Book Company. New York, New York.
- Spzak, E. and F. G. Rice, 1975. New insights on the strength of polyethylene piping. AWWA 95th Annual Conference. Minneapolis, Minnesota.

- Stoner Associates, 1981. LIQT users guide. Carlisle, Pennsylvania.
- Timoshenko, T., 1940. Strength of materials, Part II. Van Nostrand. New York, New York.
- Uni-Bell, 1982. Handbook of PVC pipe--design and construction. Uni-Bell Plastic Pipe Association. Dallas, Texas.
- Vennard, J. K. and R. L. Street, 1975. Elementary fluid mechanics. John Wiley and Sons. New York, New York.
- Watters, G. Z., 1971. The behaviour of PVC pipe under the action of water hammer pressure waves. PRWG-93. Utah State University. Logan, Utah.
- Watters, G. Z., R. J. Jeppson and G. H. Flammer, 1976. Waterhammer in PVC and reinforced plastic pipe. ASCE, Journal of the Hydraulics Division. Volume 102, Number 7.
- Watters, G. Z., 1979. Modern analysis and control of unsteady flow in pipelines. Ann Arbor Science. Ann Arbor, Michigan.
- Weast, R. C. (editor), 1971. Handbook of chemistry and physics--51st edition. The Chemical Rubber Company. Cleveland, Ohio.
- Wylie, E. B. and V. L. Streeter, 1978. Fluid transients. McGraw-Hill Book Company. New York, New York.
- Yarwood, T. M. and F. Castle, 1968. Physical and mathematical tables. MacMillan and Company. London, England.

B. American Water Works Association (AWWA) Standards

- C101-77. Thickness design of cast-iron pipe.
- C104-80 Cement-mortar lining for cast-iron and ductile-iron pipe and fittings for water.
- C106-75 Cast-iron pipe centrifugally cast in metal molds, for water or other liquids.
- C108-75 Cast-iron pipe centrifugally cast in sand-lined molds, for water or other liquids.
- C150-81 Thickness design of ductile-iron pipe.

- C151-81 Ductile-iron pipe, centrifugally cast in metal molds or sand-lined molds, for water or other liquids.
- C200-80 Steel water pipe 6 inches and larger.
- C205-80 Cement-mortar protective lining and coating for steel water pipe--4 inch and larger--shop applied.
- C300-82 Reinforced concrete pressure pipe, steel cylinder type, for water and other liquids.
- C301-79 Prestressed concrete pressure pipe, steel cylinder type, for water and other liquids.
- C302-74 Reinforced concrete pressure pipe, noncylinder type for water and other liquids.
- C303-78 Reinforced concrete water pipe--steel cylinder type, pretensioned.
- C400-80 Asbestos-cement distribution pipe, 4 inch through 16 inch, for water or other liquids.
- C401-77 The selection of asbestos-cement distribution pipe, 4 inch through 16 inch, for water and other liquids.
- C402-77 Asbestos-cement transmission pipe, 18 inch through 42 inch, for water and other liquids.
- C403-78 The selection of asbestos-cement transmission and feeder main pipe, sizes 18 inch through 42 inch.
- C900-81 Polyvinyl Chloride (PVC) pressure pipe, 4 inch through 12 inch, for water.
- C901-78 Polyethylene (PE) pressure pipe, tubing, and fittings, 1/2 in. through 3 in., for water.
- C950-81 Glass-fiber-reinforced thermosetting-resin pressure pipe.

**C.American Society for Testing Materials (ASTM)
Specifications**

- B88 Seamless copper water tube.
- B241 Aluminum-alloy seamless pipe and seamless extruded tube.
- B483 Aluminum-alloy drawn tubes for general purpose applications.

D. Canadian Standards Association (CSA) Standards

B137.0 Definition and general requirements for thermoplastic piping.

B137.1 Polyethylene pipe for cold water service.

B137.3 Rigid poly (vinyl chloride) (PVC) pipe for pressure applications.

E. Manufacturer's Literature

Alloy Metal Sales Limited. Aluminum pipe and tubing.

American Brass Company. Anaconda copper tubes and fittings.

American Brass Company. Anaconda metal products.

Cabot Piping Systems, 1966. Plastic piping handbook. Louisville, Kentucky.

Canron Limited. Hyprescon concrete pressure pipe.

Crane Municipal Waterworks Catalogue. Copper tube for plumbing and heating.

DuPont of Canada Limited. Sclairpipe polyethylene pipe for engineered systems.

Grinnel Company Inc. Pipe fitters handbook. Providence, Rhode Island.

Johns-Manville Company Limited. Permastran tech data sheet permastran pipe.

Johns-Manville Company Limited. Transite ring-tite water pipe.

Scepter Manufacturing Company, 1973. PVC pipe. Scarborough, Ontario.

Tables and Figures

TABLE 2.1

PIPELINE CONSTRAINT FACTORS FOR THIN AND THICK WALLED PIPES

Equation	d/t	Pipeline Constraint Factor			Range (%)	Deviation (%)
		Case a	Case b	Case c		
Thin Walled	∞	0.950	0.910	1.000	10	0
Thick Walled	40	0.992	0.953	1.041	9	5
Thick Walled	25	1.017	0.979	1.066	9	8
Thick Walled	10	1.124	1.087	1.169	8	19
Thick Walled	5	1.312	1.278	1.353	6	40

- Notes:
1. $u = 0.30$
 2. Range is $100 (\text{maximum} - \text{minimum})/\text{minimum}$.
 3. Deviation is largest deviation from the values obtained using the thin walled formulation.

TABLE 2.2

CEMENT MORTAR LININGS FOR STEEL PIPE

Nominal Diameter (inches)	Lining Thickness (inches)	Tolerance (inches)	Maximum Celerity Increase (%)
4 to 10	1/4	-1/32 to +1/32	1.8
11 to 23	5/16	-1/16 to +1/8	3.5
24 to 36	3/8	-1/16 to +1/8	4.0
Over 36	1/2	-1/16 to +1/8	5.6

- Notes:
1. From AWWA C205.
 2. Celerity increases based on cement mortar $E = 4,420$ ksi and standard weight steel pipe.
 3. Maximum pipe size considered is 72 inch.

TABLE 2.3

CEMENT MORTAR LININGS FOR CAST AND DUCTILE IRON PIPES

Nominal Diameter (inches)	Lining Thickness (inches)	Tolerance (inches)	Maximum Celerity Increase (%)
3 to 12	1/16	+1/8	1.2
14 to 24	3/32	+1/8	1.6
30 to 54	1/8	+1/8	1.6

- Notes: 1. From AWWA C104.
2. Celerity increases based on cement mortar E = 4,420 ksi and class 50 ductile iron pipe.

TABLE 2.4

CELERITIES FOR AIR/WATER MIXTURES

V _g /V (%)	K _e (psi)	P _e (sl/ft ³)	a _e (fps)
0.0	300,000	1.940	4720
0.1	19,600	1.938	1210
0.2	10,100	1.936	865
0.5	4,140	1.930	555
1.0	2,090	1.921	395

- Notes: 1. Conditions are for 45°F and 1 atmosphere pressure.
2. Equations 2.2, 2.14 and 2.15 are used.
3. Properties for water: K_l = 300,000 psi
p_l = 1.940 sl/ft³
For air:
K_g = 21 psi
p_g = 0.00238 sl/ft³

TABLE 2.5

PROPERTIES AND SONIC VELOCITIES OF WATER

Temperature (°F)	Density (sl/ft ³)	Bulk Modulus (ksi)	Sonic Velocity (fps)	Sonic Velocity Ratio
32	1.940	287	4616	0.978
40	1.940	296	4687	0.993
45	1.940	300	4719	1.000
50	1.940	305	4758	1.008
60	1.938	313	4823	1.022
70	1.936	319	4871	1.032
80	1.934	324	4912	1.041
90	1.931	328	4946	1.048
100	1.927	331	4973	1.054
110	1.923	332	4986	1.057
120	1.918	332	4993	1.058
130	1.913	331	4992	1.058
140	1.908	330	4991	1.058
150	1.902	328	4983	1.056
160	1.896	326	4976	1.054
170	1.890	322	4953	1.050
180	1.883	318	4931	1.045
190	1.876	313	4902	1.039
200	1.868	308	4873	1.033
212	1.860	300	4819	1.021

- Notes:
1. Values for density and bulk modulus taken from Vennard and Street (1975). Properties are for conditions at atmospheric pressure.
 2. Sonic velocity ratio is comparison to sonic velocity at 45°F.

TABLE 2.6**PROPERTIES OF SOME COMMON FLUIDS**

Fluid	Temperature (°F)	Density (sl/ft ³)	Bulk Modulus (ksi)	Sonic Velocity (fps)	Celerity in 12 inch Steel Pipe (fps)
Benzene	68	1.70	150	3565	3320
Carbon Tetrachloride	68	3.08	163	2760	2555
Ethyl Alcohol	68	1.53	175	4060	3735
Glycerin	68	2.44	630	6100	4750
Kerosene	68	1.58	191	4170	3815
Mercury	60	26.26	3,800	4565	2060
Methyl Alcohol	68	1.61	176	3970	3650
Oil (viscosity 20 c/s)	72	1.53	242	4770	4270
Oil (viscosity 500 c/s)	72	1.67	271	4835	4275
Paraffin Oil	93	1.55	176	4045	3720
Water	70	1.936	319	4870	4225

- Notes:
1. Taken from Crane (1969), Pearsall (1965), Vennard and Street (1975), and Yarwood and Castle (1968).
 2. Differences in values presented for density and bulk modulus exist between sources. Therefore, the values presented here should be considered approximate.
 3. Steel pipe is standard weight; $E = 30,000,000$ psi; $\nu = 0.30$; Case b constraint and the thick walled equation.

TABLE 2.7

TYPICAL PIPELINE MATERIAL PROPERTIES

Material	Elastic Modulus (ksi)	Poisson's Ratio
Steel	30,000	0.30
Ductile Iron	24,000	0.29
Copper	17,000	0.34
Cast Iron	15,000	0.27
Aluminum	10,200	0.34
Asbestos Cement (Transite)	3,400	0.20
Concrete	4,420	0.20
Polyvinyl Chloride	425	0.40
Polyethylene	155	0.45
Wood (Douglas Fir)	1,810	-

- Notes:
1. For concrete $E = 57 \sqrt{f'_c}$ where f'_c is the 28 day compressive strength in psi (Ferguson, 1979). A value of $f'_c = 6000$ psi is used here.
 2. Elastic modulus for wood is given for wet service. It will decrease with age. Wood is not isotropic.

TABLE 2.8**MODULUS OF ELASTICITY FOR SELECTED SOILS**

Soil Description (psi)	Elastic Modulus		(E_s - psi)
Very soft clay	50	-	400
Soft clay	250	-	600
Medium clay	600	-	1,200
Hard clay	1,000	-	2,500
Sandy clay	4,000	-	6,000
Silty sand	1,000	-	3,000
Loose sand	1,500	-	3,500
Dense sand	7,000	-	12,000
Dense sand and gravel	14,000	-	28,000
Loess	14,000	-	18,000

Note: From Bowles (1968).

TABLE 2.9**MODULUS OF SOIL REACTION FOR SELECTED BEDDING MATERIALS**

Bedding Material	Dumped	< 85% Proctor	85-95% Proctor	> 95% Proctor
Fine-grained soils (LL > 50)	No data available; use E' = 0			
Fine-grained soils (LL < 50)	50	200	400	1000
Fine-grained soils (LL < 50) or Coarse-grained soils (fines > 12%)	100	400	1000	2000
Coarse-grained soils (fines < 12%)	200	1000	2000	3000
Crushed rock	1000	3000	3000	3000

Notes: 1. From AWWA C900.
2. LL = Liquid Limit.

TABLE 2.10

MODULUS OF SOIL REACTION FOR VARIOUS BEDDING TYPES

Laying Condition	Description	Design Value	Field Tests
Type 1	Flat-bottom trench; loose backfill	150	790
Type 2	Flat-bottom trench; backfill lightly consolidated to centreline of pipe	300	674
Type 3	Bedded in 4" soil; backfill lightly consolidated to crown of pipe	400	522
Type 4	Bedded in 4" soil; 80% Proctor to crown	500	1011
Type 5	Bedded in 4" soil; 90% Proctor to crown	700	1285 to 1868

- Notes:
1. From AWWA C150.
 2. Field tests are from Kennedy (1976). Four tests were carried out with Type 5 laying condition.

TABLE 2.11

MODULUS OF ELASTICITY FOR SELECTED ROCK GROUPS

Type of Rock	Er (Ksi)		
Basalt	7,000	-	13,000
Granite	4,000	-	7,000
Schist	2,000	-	5,000
Limestone	2,000	-	6,000
Sandstone	1,000	-	3,000
Shale	500	-	2,000

Note: From Bowles (1968).

TABLE 3.1

CELERITIES FOR UNLINED STEEL PIPE

Nominal Diameter (inches)	<u>Pipeline Celerity for Each Pipe Schedule Number (fps)</u>					
	10	20	40	80	STD	XS
4	-	-	4360	4455	4360	4455
5	-	-	4315	4430	4315	4430
6	-	-	4280	4420	4280	4420
8	-	4120	4235	4390	4235	4390
10	-	4000	4190	4375	4190	4315
12	-	3900	4165	4365	4125	4255
14	3840	3980	4155	4365	4080	4215
16	3755	3900	4140	4360	3980	4140
18	3670	3825	4155	4355	3940	4095
20	3590	3875	4130	4350	3875	4040
24	3450	3755	4115	4345	3755	3940
30	3445	3795	-	-	3590	3795
36	3295	3670	3940	-	3450	3670
42	-	-	-	-	3320	3555
48	-	-	-	-	3210	3450
60	-	-	-	-	3010	3265
72	-	-	-	-	2850	3105
96	-	-	-	-	2585	2850

Notes: 1. Celerities calculated using thick walled equation, Case b constraint, and water at 45°F.

2. Properties for steel: E = 30,000,000 psi
u = 0.30

TABLE 3.2

CELERITIES FOR UNLINED DUCTILE IRON PIPE

Nominal Diameter (inches)	Pipeline Celerity for Each Thickness Class (fps)						
	50	51	52	53	54	55	56
3	-	4320	4360	4390	4415	4440	4460
4	-	4260	4305	4340	4370	4395	4415
6	4075	4135	4180	4220	4255	4290	4315
8	3970	4030	4080	4125	4160	4195	4225
10	3885	3950	4000	4045	4085	4120	4155
12	3820	3880	3930	3975	4020	4055	4090
14	3760	3820	3870	3920	3960	3995	4030
16	3690	3750	3805	3850	3895	3935	3970
18	3630	3690	3745	3790	3835	3875	3910
20	3570	3635	3685	3735	3780	3820	3860
24	3475	3535	3590	3640	3685	3725	3765
30	3320	3400	3475	3540	3595	3650	3695
36	3250	3345	3425	3500	3560	3620	3675
42	3195	3300	3390	3470	3540	3600	3655
48	3155	3265	3360	3445	3520	3585	3645
54	3150	3260	3360	3445	3520	3585	3645

- Notes: 1. Celerities calculated using thick walled equation, Case c constraint, and water at 45°F.
2. Properties for ductile iron: E = 24,000,000 psi
u = 0.29

CELERITIES FOR COPPER TUBING

Nominal Diameter (inches)	Celerity (fps)	
	Type K	Type L
1	4175	4045
2	3975	3870
3	3905	3780
4	3860	3730
5	3835	3665
6	3840	3615
8	3875	3670
10	3880	3675
12	3880	3625

Notes: 1. Celerities calculated using thick walled equation, Case a constraint, and water at 45°F.

2. Properties for copper: $E = 17,000,000 \text{ psi}$
 $\nu = 0.34$

TABLE 3.4

CELERITIES FOR UNLINED CAST IRON PIPE

Nominal Diameter (inches)	Pipeline Celerity for Each Thickness Class (fps)									
	21	22	23	24	25	26	27	28	29	30
3	-	4240	4275	4305	4335	4355	4385	4410	4430	4445
4	-	4195	4230	4260	4290	4320	4350	4370	4395	4415
6	4010	4055	4095	4130	4170	4210	4240	4270	4300	4325
8	3895	3940	3985	4035	4075	4115	4150	4185	4220	4255
10	3810	3860	3915	3960	4005	4045	4085	4125	4165	4200
12	3740	3800	3855	3900	3945	3990	4035	4075	4115	4155
14	3695	3740	3795	3840	3890	3940	3990	4030	4070	4110
16	3635	3690	3740	3800	3850	3895	3945	3985	4030	4070
18	3605	3660	3720	3770	3820	3870	3920	3965	4010	4050
20	3570	3630	3690	3740	3795	3845	3895	3945	3990	4030
24	3505	3565	3620	3680	3730	3785	3835	3885	3935	3980
30	3455	3515	3575	3635	3685	3745	3800	3850	3900	3945
36	3390	3450	3510	3575	3630	3690	3750	3800	3850	3900
42	3355	3415	3480	3540	3595	3655	3715	3765	3820	3865
48	3315	3380	3440	3500	3560	3620	3680	3735	3785	3825

Notes: 1. Celerities calculated using thin walled equation, Case c constraint, and water at 45°F.

2. Properties for cast iron: E = 15,000,000 psi
u = 0.27

TABLE 3.5

CELERITIES FOR ALUMINUM PIPE

Nominal Diameter (inches)	Pipeline Celerity for Each Pipe Schedule Number (fps)						
	20	40	60	80	100	120	160
2	-	3925	-	4115	-	-	4310
3	-	3895	-	4080	-	-	4255
4	-	3790	-	4010	-	4145	4230
5	-	3700	-	3947	-	4105	4210
6	-	3630	-	3925	-	4075	4195
8	3330	3535	3710	3855	3960	4065	4180
10	3140	3460	3705	3820	3940	-	-
12	2990	3410	3665	3805	-	-	-

Notes: 1. Celerities calculated using thin walled equation, Case c constraint, and water at 45°F.

2. Properties for aluminum: E = 10,200,000 psi
u = 0.34

TABLE 3.6

CELERITIES FOR ASBESTOS CEMENT (TRANSITE) DISTRIBUTION PIPE

Nominal Diameter (inches)	<u>Pipeline Celerity for Each Pipe Class (fps)</u>		
	Class 100	Class 150	Class 200
4	-	3535	3685
6	3280	3390	3540
8	3185	3280	3460
10	3100	3280	3435
12	3095	3240	3405
14	3035	3225	3380
16	3020	3195	3380
18	3005	3230	3465
20	3000	3225	3465

Notes: 1. Celerities calculated using thick walled equation, Case c constraint, and water at 45°F.

2. Properties for transite: $E = 3,400,000$ psi
 $u = 0.20$

TABLE 3.7

CELERITIES FOR ASBESTOS CEMENT (TRANSITE) TRANSMISSION PIPE

Nominal Diameter (inches)	Pipeline Celerity for Each Pipe Class (fps)								
	30	35	40	45	50	60	70	80	90
14	2700	2740	2780	2940	3020	3220	3270	3375	3465
16	2680	2750	2825	2940	3010	3190	3265	3375	3465
18	2620	2685	2910	2925	2995	3140	3265	3375	3465
20	2615	2710	2905	2925	2985	3155	3265	3375	3465
24	2610	2665	2875	2915	2980	3135	3265	3375	3465
30	2610	2665	2865	2910	2980	3140	3265	3375	3465
36	2610	2665	2865	2910	2980	3135	3265	3375	3465

- Notes: 1. Celerities calculated using thick walled equation, Case c constraint, and water at 45°F.
2. Properties for transite: $E = 3,400,000$ psi
 $u = 0.20$

TABLE 3.9

CELERITIES FOR POLYETHYLENE PIPE

Series	Pipe Diameter (inches)		
	< 8	8	10 to 48
45	695 (730)	695 (730)	655 (690)
60	790 (820)	790 (820)	745 (775)
80	895 (930)	895 (930)	850 (880)
100	985 (1030)	935 (970)	935 (970)
125	1080 (1145)	1030 (1080)	1030 (1080)
160	1190 (1290)	1135 (1215)	1135 (1215)

- Notes: 1. Celerities are for unburied pipe, calculated using thick walled equation, Case b constraint, and water at 45°F.
2. Bracketed values are estimated celerities of pipe buried in soil with $E' = 3,000$ psi.
3. Properties for polyethylene: $E = 155,000$ psi
 $u = 0.45$

TABLE 4.1

ELASTIC MODULUS FOR PLANK DECKING BY SPECIES GROUP

Species Group	Commercial Designation	<u>Modulus of Elasticity (psi)</u>	
		Dry Service	Wet Service
A	Douglas fir	1,930,000	1,310,000
	Larch	1,740,000	1,630,000
B	Hem-fir	1,620,000	1,520,000
		1,460,000	1,370,000
C	Eastern hemlock	1,400,000	1,320,000
	Tamarack	1,260,000	1,180,000
	Jack Pine		
	Pacific Coast Yellow Cedar		
D	Coast Sitka Spruce	1,350,000	1,270,000
	Ponderosa Pine	1,220,000	1,150,000
	Spruce-Pine-Fir		
E	Eastern White Pine	1,210,000	1,140,000
	Red Pine	1,080,000	1,020,000
	Western Cedars		
	Western White Pine		

Notes: 1. From LTIC (1972).

2. Dry Service conditions apply where the average equilibrium moisture content over a year is 15% or less.

3. For each designation and service condition the first value is for Select Grade and the second value is for Commercial Grade.

TABLE 4.2**CCELERITIES FOR CONTINUOUS WOOD STAVE PIPE**

Pipe Diameter (ft)	Typical Stave Thickness (in)	Typical Band Size (in)	Pipeline Celerity (fps)		
			Lower Limit	Parmakian Method	Upper Limit
2	1.500	0.375	970	1675	2535
2	1.500	0.500	1270	1835	2610
3	1.625	0.500	1050	1570	2305
4	1.625	0.625	1135	1520	2135
5	2.625	0.625	1020	1540	2275
5	2.625	0.750	1210	1655	2335
6	2.625	0.750	1110	1525	2175
7	2.625	0.750	1035	1425	2045
8	2.625	0.750	970	1340	1935
8	3.625	0.825	1065	1510	2180
9	3.625	0.825	1005	1430	2080
10	3.625	0.825	955	1365	1995
12	3.625	0.825	875	1250	1850
14	3.625	0.825	810	1165	1730
16	4.625	1.000	915	1265	1835
18	4.625	1.000	865	1200	1745

- Notes:
1. Celerities calculated using thin walled equivalent pipe equation, Case c constraint, and water at 45°F.
 2. Properties for steel bands: $E = 30,000,000$ psi spaced at 10inches.
 3. Properties for wood: $E = 1,810,000$ psi.
 4. Typical dimensions from Morrison (1959).

TABLE 4.3

CELERITY RANGE FOR CONTINUOUS WOOD STAVE PIPE

Diameter (ft)	Band Spacing (in)	Working Pressure (psi)	Pipeline Celerity (fps)		
			Lower Limit	Parmakian Method	Upper Limit
2	10	33	1270	1835	2610
	1.9	173	2555	2750	3120
18	10	15	865	1200	1745
	2.1	69	1780	1930	2240

- Notes: 1. Celerities determined as in Table 4.2.
2. Working pressures based on steel stress of 20,000 psi.

TABLE 4.4

CCELERITIES FOR CONCRETE PRESSURE PIPE

Nominal Diameter (inches)		<u>AWWA C300</u>			<u>AWWA C301 (embedded)</u>			<u>AWWA C301 (lined)</u>		
		100	150	200	100	150	200	100	150	200
24	Maximum	3920	3970	4010	3830	3840	3850	3780	3800	3810
	Minimum	3880	3610	3630	3400	3370	3330	3380	3360	3350
30	Maximum	3790	3860	3920	3680	3700	3710	3730	3740	3750
	Minimum	3490	3430	3520	3180	3150	3130	3310	3280	3270
36	Maximum	3770	3840	3890	3550	3570	3590	3680	3690	3830
	Minimum	3410	3390	3490	3030	2980	3010	3250	3230	3280
42	Maximum	3750	3820	3880	3520	3530	3550	3640	3660	
	Minimum	3360	3370	3470	2960	2910	2960	3200	3170	
48	Maximum	3720	3810	3870	3490	3510	3520	3610	3660	
	Minimum	3320	3350	3460	2870	2860	2910	3150	3270	
54	Maximum	3720	3790	3860	3660	3680	3700			
	Minimum	3290	3330	3450	3010	2930	2950			
60	Maximum	3710	3780	3850	3640	3650	3680			
	Minimum	3270	3320	3440	2950	2880	2940			
66	Maximum	3710	3780	3850	3630	3640	3680			
	Minimum	3260	3310	3440	2920	2850	2990			
72	Maximum	3690	3770	3840	3630	3640	3670			
	Minimum	3250	3310	3440	2980	2900	2960			
78	Maximum	3690	3770	3840						
	Minimum	3240	3300	3430						
84	Maximum	3680	3760	3830						
	Minimum	3230	3300	3430						

Note: Taken from Kennison (1956).

TABLE 4.5

CELERITIES FOR PERMASTRAN PIPE

Nominal Diameter (inches)	Celerity (fps)
4	1725
6	1575
8	1520
10	1565
12	1575

- Notes: 1. From Johns-Mansville (1977).
2. Values are for Class 200 pipe and water at 60°F.

TABLE 4.6

TYPICAL TUNNEL CELERITIES

Rock Elastic Modulus (ksi)	With ½ Inch Steel Liner			
	Unlined	25 Ft	10 Ft	5 Ft
1,000	3535	3630	3745	3890
2,500	4120	4145	4175	4225
5,000	4390	4395	4405	4425
7,500	4490	4495	4500	4510
10,000	4545	4545	4550	4555

- Notes: 1. Celerity for water at 45°F.
2. Properties for steel: E = 30,000 ksi
u = 0.30
3. u = 0.30 for rock.

TABLE 5.1

SUMMARY OF CELERITY EQUATION APPLICATIONS

Pipe Material	Thin Walled Deviation (%)	Celerity Range (fps)	Comments
Steel	0.8	2585 - 4455	Consider lining effects
Ductile Iron	1.0	3150 - 4460	Can use thin walled equations
Copper	1.3	3625 - 4175	Can use thin walled equations
Cast Iron	1.6	3315 - 4445	Can use thin walled equations
Aluminum	2.3	2990 - 4310	Can use thin walled equations
Transite	4.4	2610 - 3685	Use thick walled equations
PVC	7.6	900 - 1610	Consider burial effects
Polyethylene	17.0	655 - 1290	Consider burial effects
Wood Stave	n/a	1200 - 2750	Equivalent steel composite pipe.
Concrete	n/a	2850 - 4010	Equivalent steel composite pipe
Permastran	n/a	1575 - 1725	Use Manufacturer's data
Unlined Tunnels	n/a	3535 - 4545	Rock properties variable and uncertain
Lined Tunnels	n/a	3630 - 4555	Rock properties variable and uncertain

- Notes:
1. Thin walled deviation is the maximum increase to be expected if the thin walled equation is used instead of the thick walled equation.
 2. Celerity range is based on sizes and classes of commercial pipe examined.

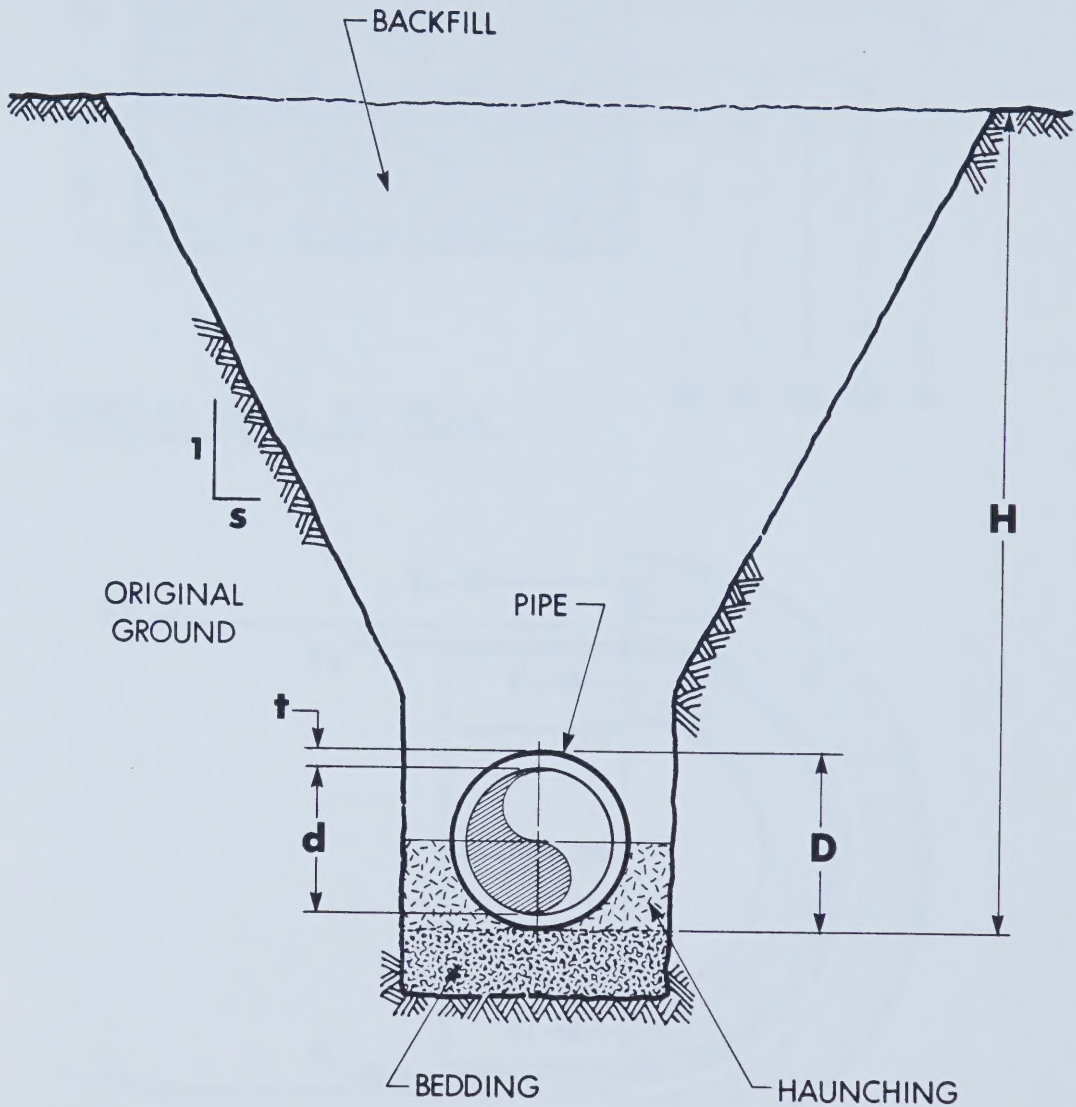


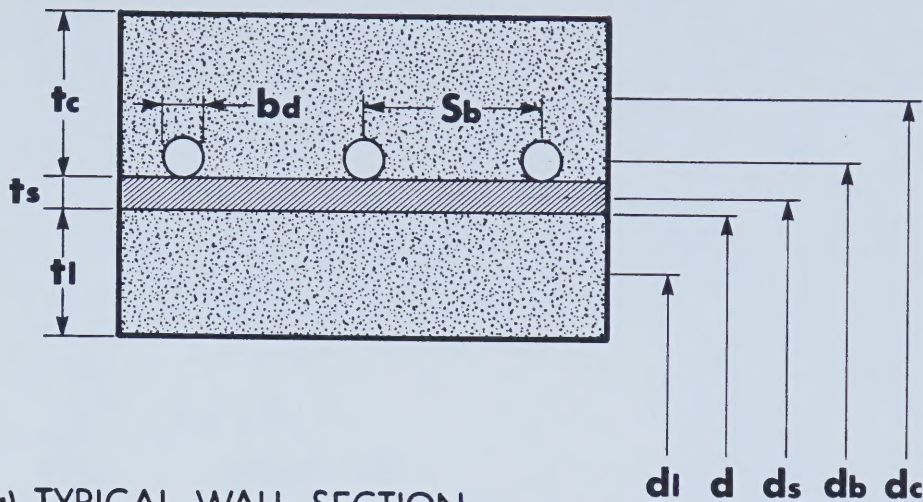
figure 1

TYPICAL PIPE INSTALATION

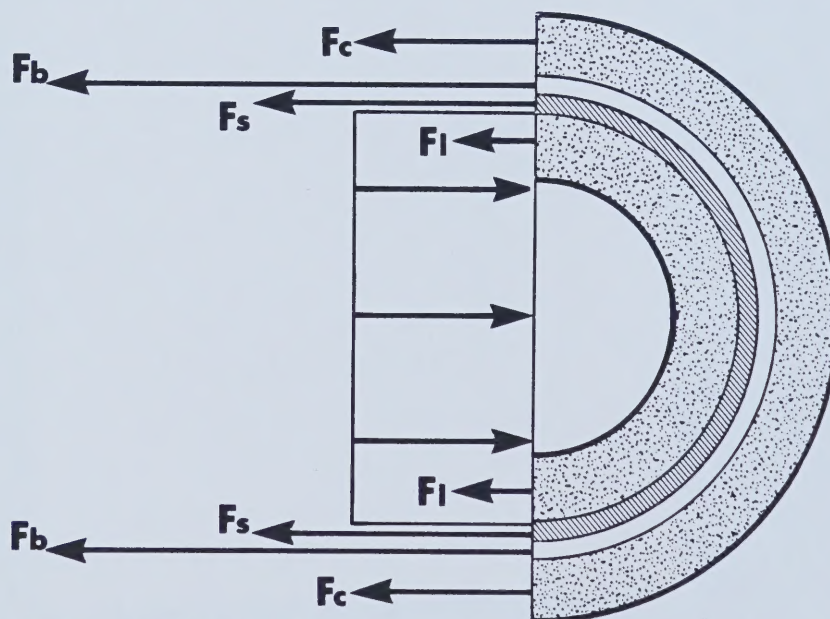


Stanley

STANLEY ASSOCIATES ENGINEERING LTD.



a) TYPICAL WALL SECTION



b) FORCES AT LOW PRESSURE

figure 2

CONCRETE PRESSURE PIPE FORCE BALANCE



Stanley

STANLEY ASSOCIATES ENGINEERING LTD.

E5114

Hodgson, J.E.

Pipeline Celerities

E5114

